

Armed Services Technical Information Agency

AD

19598

NOTICE: WHEN GOVERNMENT OR OTHER DRAWINGS, SPECIFICATIONS OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY RELATED GOVERNMENT PROCUREMENT OPERATION, THE U. S. GOVERNMENT THEREBY INCURS NO RESPONSIBILITY, NOR ANY OBLIGATION WHATSOEVER; AND THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED, FURNISHED, OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA IS NOT TO BE REGARDED BY IMPLICATION OR OTHERWISE AS IN ANY MANNER LICENSING THE HOLDER OR ANY OTHER PERSON OR CORPORATION, OR CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

Reproduced by
DOCUMENT SERVICE CENTER
KNOTT BUILDING, DAYTON, 2, OHIO

CONFIDENTIAL

The following ESPIONAGE NOTICE can be disregarded unless this document is plainly marked RESTRICTED, CONFIDENTIAL, or SECRET.

NOTICE: THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 and 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

Bell/Rep. 106-989-001

86561
19598

SHIP MOTION



BEST
AVAILABLE COPY

BELL

CORPORATION

REPORT NO. 106-989-001

INDEX NO. 010221

SHIP MOTION

PROPERTY OF R.D.
TECHNICAL LIBRARY

by

David G. Williams
Campbell E. Hills
Herbert Mennen
John P. Chisholm

BELL *Aircraft* CORPORATION

JULY 1953

This report covers work performed under
Contract NObsr 52476 with the Bureau of Ships.

NOTICE: This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Sections 793 and 794. The transmission of this document or the revelation of its contents in any manner to any unauthorized person is prohibited.

REPORT NO. 106-989-001

CONFIDENTIAL

SECURITY INFORMATION—CONFIDENTIAL



REPORT NO. 106-989-001

CONFIDENTIAL

table of contents

Section	Page
Abstract	1
I Introduction	2
II Terms and History	11
III Planning	19
IV Instrumentation	23
V Accuracy	31
VI Typical Installation	39
VII Data Analysis I	63
VIII Data Analysis II	99
IX Vibration and Slam	115
X Supplementary Topics	139
XI Conclusion	149
Appendix I Definitions	151
Appendix II Shipboard Organization	153
Acknowledgements	159
Bibliography	160

list of illustrations

Figure		Page
1	Landing on a Carrier, Always a Tricky Maneuver, is Complicated by Ship Motion	4
2	The USS Robert L. Wilson in a Heavy Sea	5
3	A TBF Crash Aboard the USS Core; Pitching is Evidenced by . . . Relative Positions of Deck and Horizon	6
4	Crash Shown in Figure 3 . . . Viewed From the Starboard Catwalk	7
5	Airplanes on the Flight Deck of the USS Core during a North Atlantic Storm	8
6	Morning Quarters on a Rolling Deck	9
7	Violent Pitching of USS Lunga Point, Off Wakayama, Japan. Pitch Motion is Estimated to be $\pm 6^\circ$	10
8	USS Philippine Sea, Plowing Into a Storm Wave	13
9	An FM-2 Crashes the Port Stacks on the USS Core	17
10	Block Diagram of a Typical Recording Installation	18
11	Representative Recording and Playback Equipment	24
12	Sensing Instruments - USS Oriskany Installation	33
13	Recording Instruments - USS Oriskany Installation	40
14	Stable Element - USS Oriskany Installation	41
15	Accelerometers Mounted on Unstabilized Mount (left) and One-Axis Stable Table (right)	43
16	Rate Gyro and Mount	45
17	Synchro-Driven Potentiometers	47
18	Equipment Racks at Main Recording Site	50
19	Rack-Mounted Equipment at Main Recording Site	51
20	Signal Filter Panel	52
21	Sensitivity Control Panel	53
22	Meter Panel	54
23	Calibrate-Operate Panel	55
24	Discriminator Connection Panel	56
25	Sub-Carrier Oscillator Mounting Panel	57
26	Voltage Adjustment Panel	58
27	Tape Recorder and Constant-Frequency Capstan-Drive Amplifiers	59
28	Sanborn Four-Channel Pen Recorder	60
29	Cabling Diagram - USS Oriskany Installation	61
30	Electronic Autocorrelator	65
31	Sample of Autocorrelation	67
32	Sample of Autocorrelation	68
33	Sample of Autocorrelation	69

list of illustrations

Figure		Page
34	Sample of Autocorrelation	70
35	Sample of Autocorrelation	71
36	Sample of Autocorrelation	72
37	Sample of Autocorrelation	73
38	Sample of Autocorrelation	74
39	Relation of Pitching Period to Period of Encounter	76
40	Electronic Spectrum Analysis - Method I	78
41	Samples of Amplitude Spectra	80
42	Samples of Amplitude Spectra	81
43	Samples of Amplitude Spectra	82
44	Samples of Amplitude Spectra	83
45	Pitch Motion Samples	84 - 85
46	Amplitude Spectrum of Pitch - First Three Derivatives Determined Graphically	87
47	Pitch Motion of USS Oriskany and First Three Derivatives Obtained by Differentiation	88
48	Pitch Motion of USS Oriskany and First Three Derivatives Obtained from Pitch Acceleration	89
49	Filter Section Used in Electronic Spectrum Analysis- Method II	92
50	Composite Pitch Spectrum	93
51	Pitch Spectrum Determined from Stable Element	94
52	Pitch Spectrum Determined from Pitch Acceleration	95
53	Pitch Spectrum Determined from Pitch Acceleration	96
54	Methods of Determining Transfer Function	100
55	Spectrum of Ship Compared to Transfer Function of Ship	102
56	Determination of Natural Period of Ship	104
57	Accelerometer Connections and Typical Record from Towing Tests	105
58	Response of USS Coral Sea, Determined by Model Tests	106
59	Maximum Forward Acceleration as a Function of Frequency of Encounter	107
60	Results of Model-Towing Test	108
61	Results of Model-Towing Test	109
62	Pitching Period Versus Period of Encounter	110
63	Relation of Wave Length, Period, and Velocity	112
64	Conversion from Acceleration to Displacement	113
65	Slam!	117

list of illustrations

Figure		Page
66	Another Example of Slam - USS Saratoga	118
67	Output of Filters Showing Distribution of Energy Between First and Second Modes	121
68	A Half-Hour Record of the Motion of the USS Oriskany	122
	. . . Recorded During a Storm Off Cape Horn	123
69	A Half-Hour Record of the Motion of the USS Oriskany	124
	. . . Recorded During a Storm Off Cape Horn	125
70	Slam in an Apparently Calm Sea	126
71	Comparison of Pitch and Acceleration During Slam	127
72	Slam Vibrations Damped by Subsequent Slam	128
73	Acceleration at Frequencies of First Two Modes as a Function of Total Acceleration	131
74	Acceleration at Frequencies of First Mode as a Function of Total Acceleration	132
75	Acceleration at Frequency of Second Mode as a Function of Total Acceleration	133
76	Peak Acceleration at Frequency of First Mode as a Function of Total Acceleration	134
77	Number of Slams Occurring in One Half-Hour as a Function of Total Acceleration	135
78	Spray Probably Caused by a Slam	136
79	Typical Slam Records Used to Determine the Q of the Ship	137
80	USS Santee in a Storm	138
81	Pitch Motion of USS Wasp During Aircraft Recovery	141
82	Aft Acceleration of USS Wasp	142
83	Method of Determining Pitch Acceleration	144
84	Method of Determining Average Vertical Acceleration	144
85	Average Vertical Acceleration	145
86	Roll Spectrum	147
A-1	Pitch Angle and Roll Angle	150
A-2	Typical Shipboard Organization Chart	155

tables

Table 1.	Stable Element Characteristics	26
Table 2.	Synchro Motor and Generator Characteristics	35
Table 3.	Equipment List	49
Table 4.	Frequencies of Principal Modes	119

abstract

This report is an account of the ship-motion recording program carried out by the Bell Aircraft Corporation as a part of the All Weather Carrier Landing Project. The recording installation on the U.S.S. Oriskany is described, and samples of motion recorded on this and on other ships are presented with discussion of the methods and results of analysis. Although the reduction of the data has, of necessity, been directed toward a specific program, every effort has been made to keep the discussion and presentation general. Additional analyses, unnecessary for this program, have been performed and are included in certain cases where it was felt they would interest the majority of readers. With the aim of assisting others who are undertaking ship motion recording programs for similar or for other purposes, detailed information on data sources aboard ship, instrumentation, accuracy of measurement, and shipboard organization is presented in as general a manner as possible.

section I introduction

Although marine transportation is almost as old as man himself, one of the most important and fundamental problems remains essentially unsolved. This is the ship-motion problem. Limited solutions which treat the effect have been achieved by means of such devices as lashings, gimbal rings, and stable elements. More general solutions, utilizing gyros or retractable fins to develop forces opposing the motion, have been attempted with reasonable success. As yet, however, there is no complete solution - some device which would maintain the ship perfectly level, or a hull design which would be stable under all surface conditions. For the present, the ship motion problem must be recognized as an inherent consideration in the design of almost every item carried on a ship, and in the planning and execution of every operation carried out aboard a seagoing vessel. The landing of airplanes on an aircraft carrier, commonly called the recovery operation, is no exception; and it is for this reason that ship motion is a major concern to the project under which the study recorded in this report was performed.

Ship motion, as it affects the recovery operation, is in reality a twofold problem. The incoming pilot is faced with the uncertainty of the future position of the landing area. Furthermore, an attempt to land on a violently pitching deck while the landing area is rising could result in severe damage to the airplane. An adequate solution of the ship-motion phase of the carrier landing problem must resolve both these difficulties.

In general, the two logical approaches to this problem are the same ones that have been used in the past: to attempt to stabilize the entire ship, or at least part of it, such as the landing area; or to accept the motion and attempt to cooperate with it.

Although significant advances have been made towards stabilization of the entire ship in angular displacements, no work has been reported to date on stabilization of linear, particularly vertical, displacements. An account of several ship-stabilization systems is given in the next section. Because it was considered that angular stabilization would be inadequate, the approach to the problem has been directed to the other alternative.

Cooperation with the motion can be achieved by prediction. If the position of the flight deck were known a short time - perhaps five

seconds — in advance, the airplane could be waved off if the conditions for landing were unfavorable. If the conditions were favorable the airplane could be put on a course compatible with a landing on the predicted position of the deck.

Since the airplane would be controlled by radio link, a better solution would be to vary the plane's course and speed to insure landing at a favorable instant whenever possible. This would greatly reduce the number of deck-motion wave-offs. Whether or not this will be possible in all instances depends on the airframe response, the accuracy of the prediction, and the prediction interval. The last two factors depend directly on how well the motion of the carrier is understood.

The information on which the prediction is to be based may be acquired in two ways: by recording the motion of the ship in past time or by knowing the nature of the surface disturbance and the transfer function of the ship. Although there was no intention of neglecting the second, the former approach originally appeared more feasible for several reasons: Intensive work on wave-motion has been carried on for only a comparatively short time; the problem of obtaining the transfer function of a ship, though not insurmountable, is certainly formidable; and instrumentation currently available is better for obtaining accurate records of ship motion than for obtaining information on surface disturbance.

Having decided upon the first of these alternatives, recording and studying the motion, a search was instigated for existing ship-motion records. The only data obtained were supplied by the British Admiralty and consisted of many 220-second runs of motion recorded on a 10,000-ton cargo vessel. As this was not considered adequate, a program was initiated to record the motion of aircraft carriers.

This report deals principally with the ship-motion recording program and the subsequent data analysis. The prediction problem is treated only as necessary to explain why certain methods of analysis were used. It will be shown how the results of the initial part of the data analysis, which was carried out on the basis of the first alternative, led to an eventual consideration of the data on the basis of the second, involving determination of the transfer function by model-basin studies.



Figure 1. Landing on a Carrier, Always a Tricky Maneuver, is Complicated by Ship Motion



Figure 2. The USS Robert L. Wilson in a Heavy Sea



Figure 3. A TBF Crash Aboard the USS Core; Pitching is Evidenced by . . .



Relative Positions of Deck and Horizon

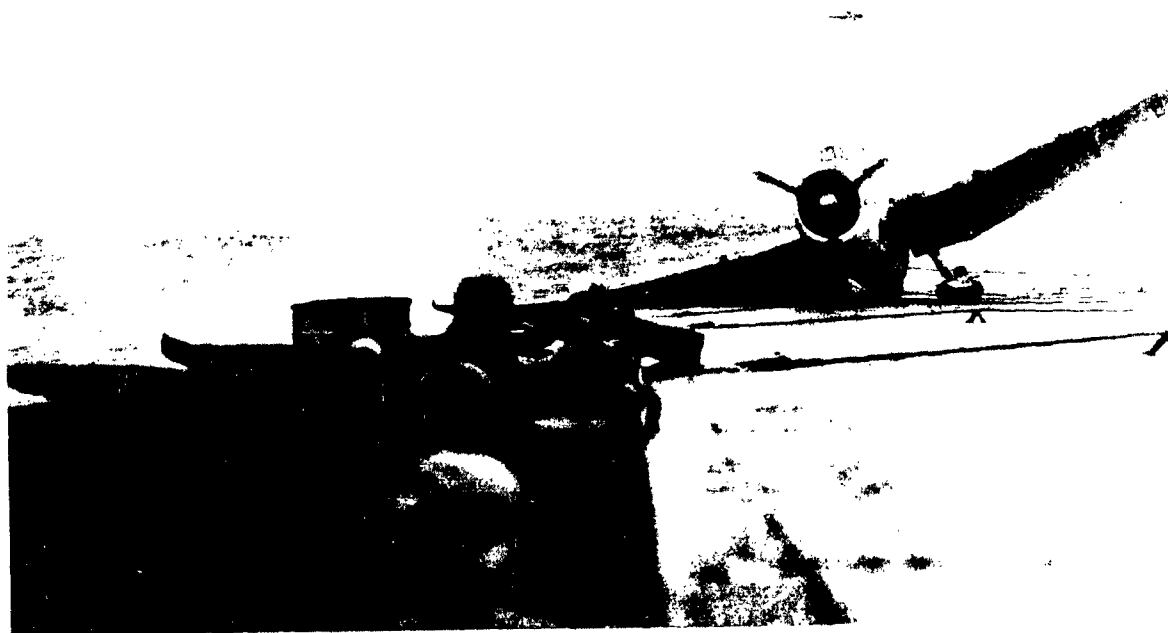


Figure 4. Crash Shown in Figure 3 . . .



Viewed From the Starboard Catwalk



Figure 5. Airplanes on the Flight Deck of the USS Core During a North Atlantic Storm

section II terms and history

The purpose of this section is to introduce and to explain certain terms used to describe ship motion, and to discuss briefly some of the past attempts at stabilization or compensation.

A ship has three angular and three linear degrees of freedom. The former are termed "roll", "pitch", and "yaw" and the latter are termed "heave", "surge", and "sway". Standard definitions of roll and pitch are given in the appendix since these are the components of the motion which are of greatest concern in the carrier landing problem. Yaw is considered as rotation about a vertical axis. Heave, surge, and sway are taken as translations in the vertical, longitudinal and lateral directions respectively.

The axes of rotation of the angular motions do not remain stationary, hence there is no point which could be called the center of the angular motions. It has been convenient to designate some arbitrary point — frequently the center of gravity — as the center of the angular motions and restrict the use of the terms heave, surge, and sway to the translations of this point. Linear motions of all other points are spoken of simply as displacements. Another point which it is frequently convenient to designate as the center of angular motions is a point two-thirds of the distance from the forward to the aft perpendicular. It will be shown (Section X) that the average vertical acceleration is a minimum at this point.

It is apparent that the motion of a ship in a seaway is a complicated phenomenon. Complete separation and measurement of the six components is an extremely difficult task; however, the angular components may be separated fairly simply by the use of gyros. For this reason most attempted solutions of the ship motion problem in the past have been limited to stabilization with respect to the angular components.

SECURITY INFORMATION—CONFIDENTIAL

A few stabilization devices have been used which make no attempt at separation of the motion into its components. Bilge keels are probably the simplest and most common. These longitudinal fins require no up-keep and never get out of order except when bent or knocked off by the ship's running aground. On the other hand they are not too effective, and reduce the ship's speed considerably.

One of the earliest systems incorporating separation of an angular motion, roll, in this case, was composed of ballast tanks interconnected through pumps which were controlled by a pendulum, gyro, or some other position-sensitive device. In operation, the ballast liquid was pumped from one tank to another in such a way as to increase the righting couple by shifting the center of mass. Size and erratic operation of the stabilizing equipment were the principal drawbacks of this method.

Gyro stabilizers are massive but have proved a fairly effective means of roll stabilization. The largest installation to date is the one made by the Sperry Corporation in the Italian liner Conte di Savoia. Three gyro units, each having a 100-ton flywheel 13' in diameter, comprised the bulk of the installation. These units, which rotated at speeds of from 800 to 910 rpm, were torqued by electric motors which were, in turn, controlled by small sensing gyros. The sense of the applied torque was such that the resulting precessional torque applied a righting couple to the ship.

Some significant figures pertaining to the installation and its performance are:

Ship Length	- 800 feet
Beam	- 96 feet
Draft	- 30 feet
Displacement tonnage	- 41,000 tons
Metacentric Height	- 2.2 feet
Roll Period	- 24 seconds
Twisting Torque (design figure)	- 1.6×10^6 ton feet
Engine horsepower at 27 knots (cruising speed)	- 120,000 hp.

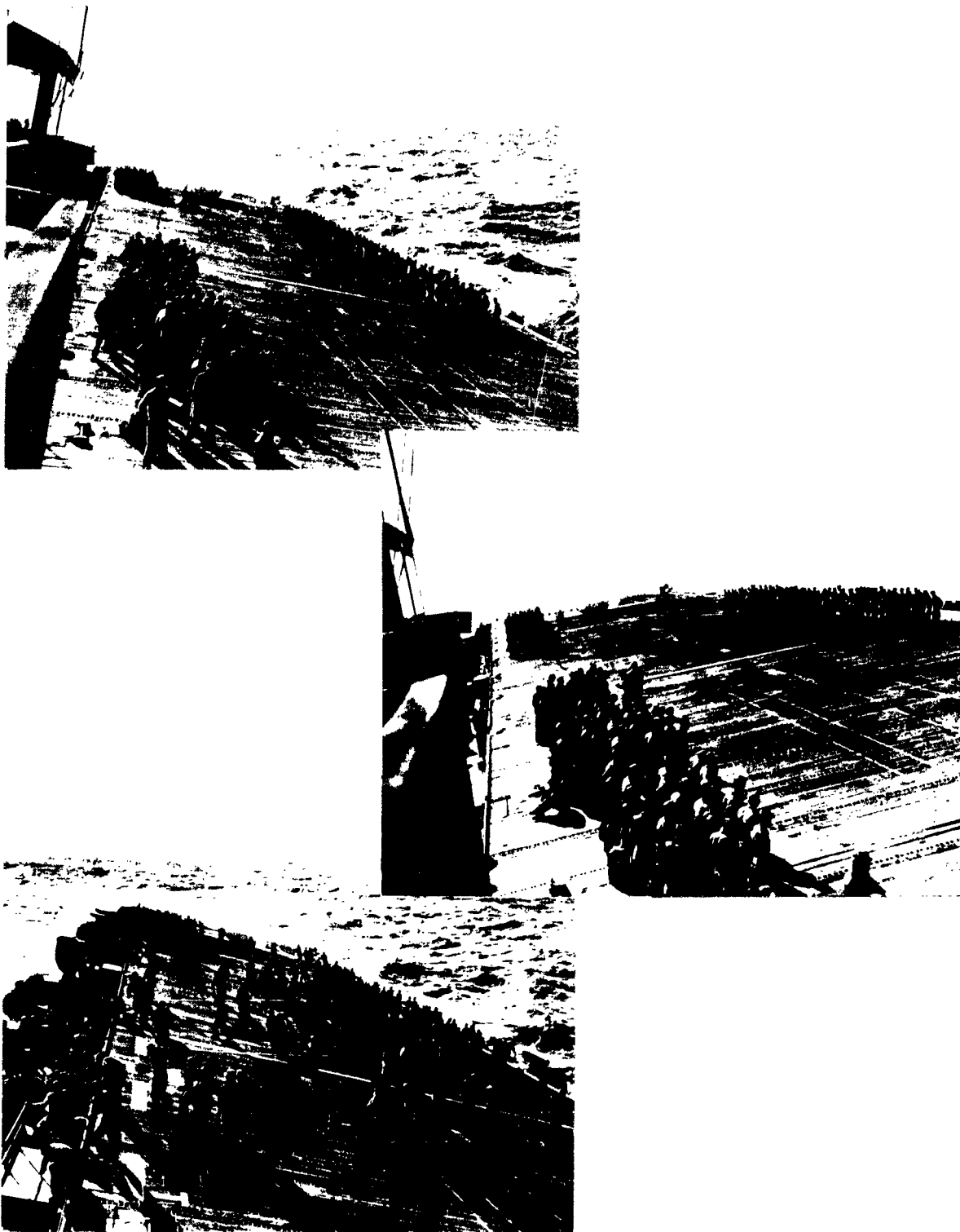


Figure 6. Morning Quarters on a Rolling Deck

SECURITY INFORMATION—CONFIDENTIAL

Gyro Installation:

Total weight	- 660 tons
Maximum stabilizing torque	- 7,860 ton feet
Power Consumption	- 1,000 hp.
Cost	- \$7,000,000

Typical performance

Max. roll) unstabilized	- 15°
Aver. roll)	- 7.5°
Max. roll) stabilized	- 2.5°
Aver. roll)	- 1.8°

Data were taken over two consecutive five-minute periods. Roll figures are for peak-to-peak roll.

The principal disadvantages of such an installation as a solution to the present problem are undoubtedly the size of the equipment and the lack of pitch stabilization. Space is limited aboard ships, particularly naval vessels, and the space requirements would make installation in existing ships a practical impossibility. No information has been received as to whether pitch stabilization by gyros has been attempted.

Stabilization by means of controllable fins is currently being investigated by the British. No authoritative data have been received on the performance of recent experimental installations, but from unofficial reports, the system appears to have considerable promise. The most complete information which is available concerns an earlier installation aboard the T.S.S. Isle of Sark in 1936. A single retractable fin, 34 square feet in area, was located on each side of the ship, approximately at the center of the curve of the bilge. When the ship rolled the fins could be rotated, or canted, about an axis through the center of pressure of each in such a way that water pressure, due to the forward motion of the ship, produced a torque which tended to right the ship. The motors which accomplished the rotation were controlled by gyros. At a speed of 19 knots, 20° peak-to-peak rolling was reduced to 4°, while the reduction in speed was only 0.25 knots. It is interesting that the reduction of rolling was independent of the unstabilized roll amplitude and depended only on the physical dimensions and tilt angle of the fins, and on the ship's speed. The controlling mechanism was actuated by roll angular velocity rather than displacement, thus the effect of the fins was to stabilize the ship about a mean position rather



Figure 7. Violent Pitching of USS Lunga Point, off Wakayama, Japan.
Pitch Motion is Estimated to be $\pm 6^\circ$

than about an arbitrary one. If the ship had a constant 5° list in still water for example, the fins would tend to stabilize the ship in this position rather than in an upright one.

This method appears to offer the most promise of any of the ship-stabilization systems, particularly since unofficial reports indicate that some degree of pitch stabilization is achieved. One disadvantage might arise from the fact that the reduction of rolling varies as a direct function of the ship's speed. During aircraft recovery operations the ship's speed is determined by the required wind velocity across the deck. Although some latitude is permitted as far as the necessary relative wind velocity is concerned, it might happen that the two conditions on the ship's speed were incompatible. For example, if the true wind speed were thirty-five knots and twenty knots ship speed were required for adequate stabilization, the wind across the deck would be fifty-five knots. In general, landings cannot be successfully accomplished in winds this great, because of deck-handling difficulty.

There is one other attempted solution of the ship motion problem which is worth noting. This one is of particular interest because it was applied to the carrier-landing problem and involves prediction.

In the course of informal discussions with researchers working on similar projects for the British Admiralty it was learned that prediction of the motion of the landing area by a human observer had been attempted by the British.

An officer stationed at the bow would observe the approaching waves and attempt to predict the motion. His prediction was given directly to the Landing Signal Officer by telephone. No significant success was achieved and the plan was discontinued. It was believed that the failure of the scheme was due to wave interference effects occurring within the length of the ship. Information is not readily available pertaining to other attempts to predict ship motion directly on the basis of surface observation.

Although some of the systems described in the preceding paragraphs show promise of future application to the carrier landing problem, none can be currently considered adequate. The next section of this report deals with the processes of data accumulation for a study which, it is hoped, will lead to a satisfactory solution.

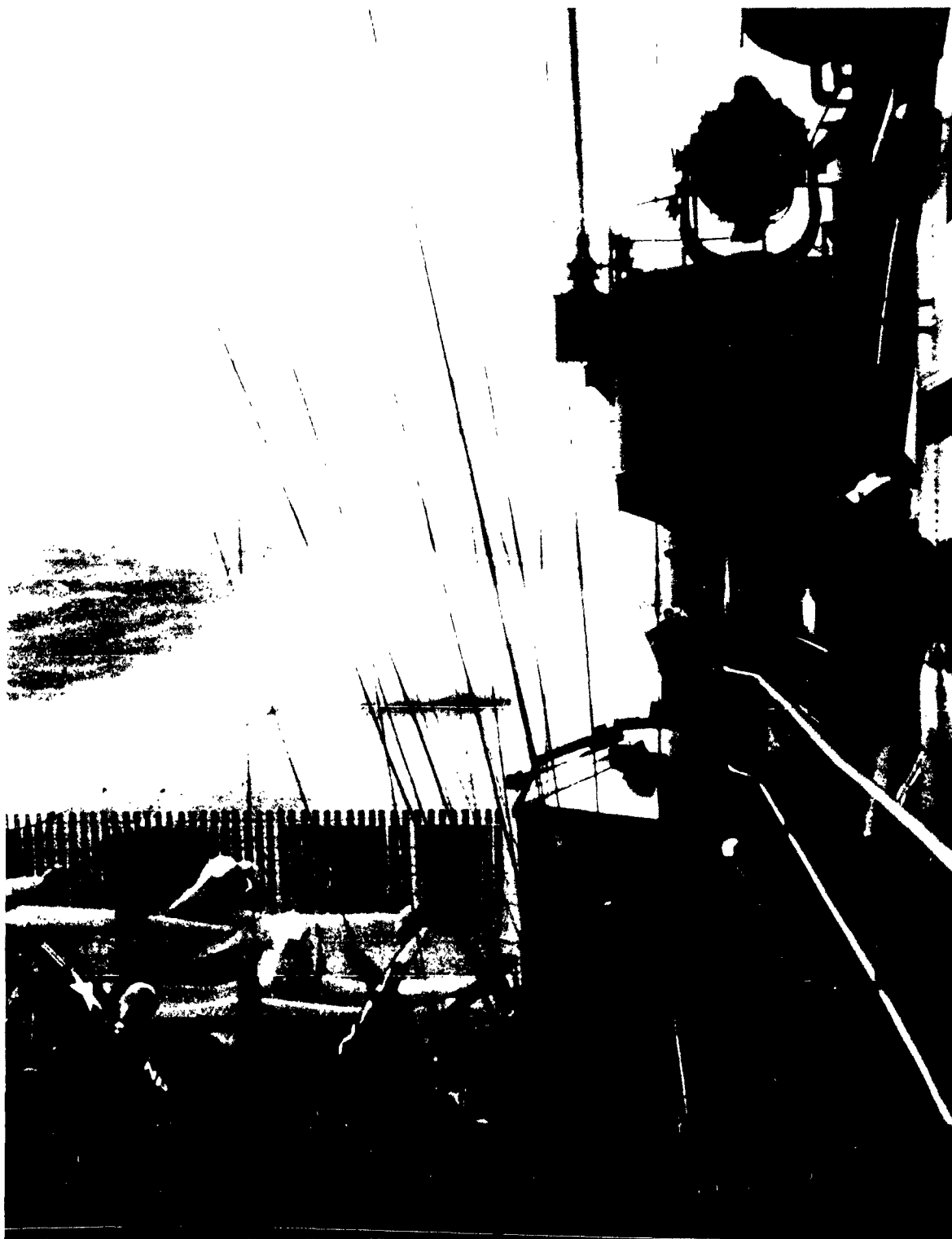


Figure 8. USS Philippine Sea, Plowing into a Storm Wave



Figure 9. An FM-2 Crashes the Port Stacks on the USS Core

section III planning

The initial planning of a ship-motion recording trip may be divided into two phases, first, the theoretical phase, at which time decisions must be made regarding what motions and components are to be recorded, what other information is to be gathered and what additional work, such as data reduction, is to be carried out aboard ship. Second, the practical phase, encompassing the materiel aspects such as the design and construction of special equipment, layout of the recording installation, and arrangement for the running of additional cables.

The decisions which must be made during the theoretical stage of the planning depend almost entirely on the nature of the problem for which the study of ship motion is being undertaken. A ship has three angular and three linear degrees of freedom. These six variables together with their first and second derivatives constitute a total of eighteen quantities, any or all of which might be of interest. The various motions and components may be divided into three groups. Those which may be neglected, those which are unimportant as far as the problem is concerned, but are important for the effect they have on other instruments, and those which are important because of their direct bearing on the problem. Frequently the classification into these groups of at least some of the motions cannot be definitely made until the motions have been recorded and carefully studied. For example, in this particular problem the effect of heave -- the point of minimum average vertical acceleration being designated the center of angular motion -- has not as yet been fully determined. Rather than limit the recorded data to a few motions which are considered important at the initial stages of attack on a problem, it is probably a safer course to record as many different quantities as possible at first and gradually discard the ones which do not prove applicable to the problem at hand.

Although it has proved desirable to record as much information from as many different sensing sources as possible, it has not been advisable to attempt too much additional work. A ship is not an ideal

SECURITY INFORMATION—CONFIDENTIAL

laboratory nor is it an ideal place to maintain electronic equipment. If the recording group consists of one or two men, it is highly probable that all their time will be taken up in servicing and operating the recording equipment. If the problem requires a study of ship motion which is to be at all complete, it is doubtful if adequate data can be gathered on a single trip. As the program progresses, additional assignments may be made as the members of the recording group are able to handle them.

The principal difficulty which was encountered in adequately planning a ship-motion recording trip was lack of time. The equipment was usually hastily assembled; on occasion the location of the recording equipment was not decided on until the recording group boarded the ship at the beginning of the trip, and only once was it possible to set up the equipment in the laboratory and test it prior to putting it aboard ship. Needless to say, the results suffered.

Assuming that sufficient time is available, it is an excellent idea to visit the ship as soon as the theoretical planning is completed. At this time the locations for the sensing instruments and the main recording equipment may be selected. The question of where the recording equipment is to be situated is a difficult one involving many considerations. The only simplifying factor is that space is usually limited aboard ship and there will not be too many sites to choose from. Although requirements will differ according to the purpose for which the motion is being studied, there are some general factors which are worth noting.

If possible, the site should be chosen so as to minimize the amount of cable which must be run. Laying cable is a difficult problem aboard ship because of the requirements for maintaining water-tight integrity. The convenient trunks and tubes, provided when a ship is built, for penetrating water-tight bulkheads are generally completely utilized and the only remaining alternatives are to cut a hole in the bulkhead or take a round-about course to a spare tube if one can be located. Fortunately there are frequently spare circuits which may be utilized and for this reason any conference with the ship's officers regarding the choice of a location for the main recording equipment should be attended by a member of the ship's interior communication crew. An idea of the amount of cable-running that may be avoided by utilization of existing spares may be gained from the cabling diagram of the installation aboard the U.S.S. Oriskany (Page 61)

If possible, the aft end of the ship should be avoided as a recording site. This is because of the excessive shaft vibrations frequently experienced. The space chosen should be one where the presence of the recording group and equipment will not interfere with the ship's

personnel in the performance of routine duties or general drills; conversely a site should not be selected where personnel traffic will interfere with recording operations. If the recording program is to be correlated with some particular phase of the ship's operations, this should be taken into account. For the purposes of this project a location in the island or on the 0-2 level was found desirable because of the ease with which the status of flight operations could be checked. A location convenient to one of the ready rooms has also been found advantageous due to the availability of weather reports, daily operation schedules, and flight plans.

It will never, in all likelihood, be possible to locate an ideal recording site but compromise locations may be utilized to good advantage. If the compartment housing the stable element is large enough, it has several advantages despite the fact it is usually located four decks down. Fourteen conductors are required to transmit two speed and thirty-six speed pitch and roll to a remote location. These are eliminated if the recording equipment is located in the stable-element compartment. Furthermore, the stable-element yoke may be observed directly to make sure that the stabilized device has not been rotated during the recording period. This point is further discussed in the section on instrumentation.

The design and construction of the recording equipment itself will not be discussed at this time except to mention a few points where divergence from usual practice is necessary. Every unit of equipment which goes aboard ship must be provided with suitable fittings for lashing. Even a large, stable object such as a storage battery, though it might not tip over, could slide across the deck, undoubtedly striking something fragile and irreplaceable. When making provisions for securing equipment, it must be kept in mind that it should be possible to remove any unit from the completed installation without disturbing the lashings on any other unit. This forethought can save much agony in case of a breakdown at sea in rough weather — when it would be particularly desirable to have motion recording equipment operable.

It should be remembered, when designing equipment, that servicing facilities aboard ship are neither as complete nor as convenient as those ashore. If equipment must be taken to a repair shop while at sea, it is liable to mean a long, arduous, hand-carry, involving a ladder or two and several escape hatches. For these reasons small units, to which trouble may easily be traced without dismounting, have proved to be the most practical.

A detailed schedule of the ship's operation during the period just prior to the trip for which the installation is being made, should be obtained as soon as possible. This schedule should include the times

SECURITY INFORMATION—CONFIDENTIAL

the ship will be tied up to the dock, when this information is known. Transfer of the recording equipment to the ship should not be attempted when the ship is at anchor if it can be avoided. When unavoidable, the safest method of transfer is by crane or boom-whip.

It has been found desirable, especially before a long trip, to complete the installation in time to make at least one short trip prior to the trip for which the installation was made. This procedure affords an opportunity to check the installation thoroughly in actual operation. Naval vessels, whenever operations permit, spend several days in port prior to a long trip, so time is usually available to make the changes and revisions considered necessary after such a trial run.

section IV instrumentation

The instruments employed to sense the motion which it is desired to record can be discussed conveniently in two groups — those instruments which are part of the ship's equipment and those which must be supplied by the recording group. Both types of instruments are shown in Figure 10, a block diagram of a representative motion-recording installation.

The most important sensing instrument that is part of the ship's equipment is the stable element. The measured motions, i.e., the pitch or roll of the ship, appear as angular motions within the stable element. For recording purposes, however, it is advantageous to transmit these motions electrically to the recording site. This transmission is done by a synchro system.

In its simplest form, a synchro system consists of a synchro-generator mechanically coupled to the shaft whose motion it is desired to transmit, a three-conductor cable connecting the stator of the synchro generator to that of the motor, and a synchro-motor whose shaft is mechanically coupled to the device which is to be actuated by the motion. The motor shaft rotates in almost exact duplication of the motion of the generator shaft.

If the motion to be transmitted is small, the mechanical coupling to the synchro-generator may involve a gear train. If the gearing ratio is such that 10° rotation of the shaft whose motion is to be transmitted causes 360° rotation of the generator shaft, and hence of the motor shaft, the system is termed a 36-speed system. Sometimes two systems are used to transmit the motion of a single shaft. Gyro compass repeaters, in particular, operate from a one-speed system and a 36-speed system. The two motor shafts in such an arrangement are geared to the gyro-repeater shaft.

The electrical outputs of a stable element are obtained from synchro-generators which are geared directly to the level and cross-

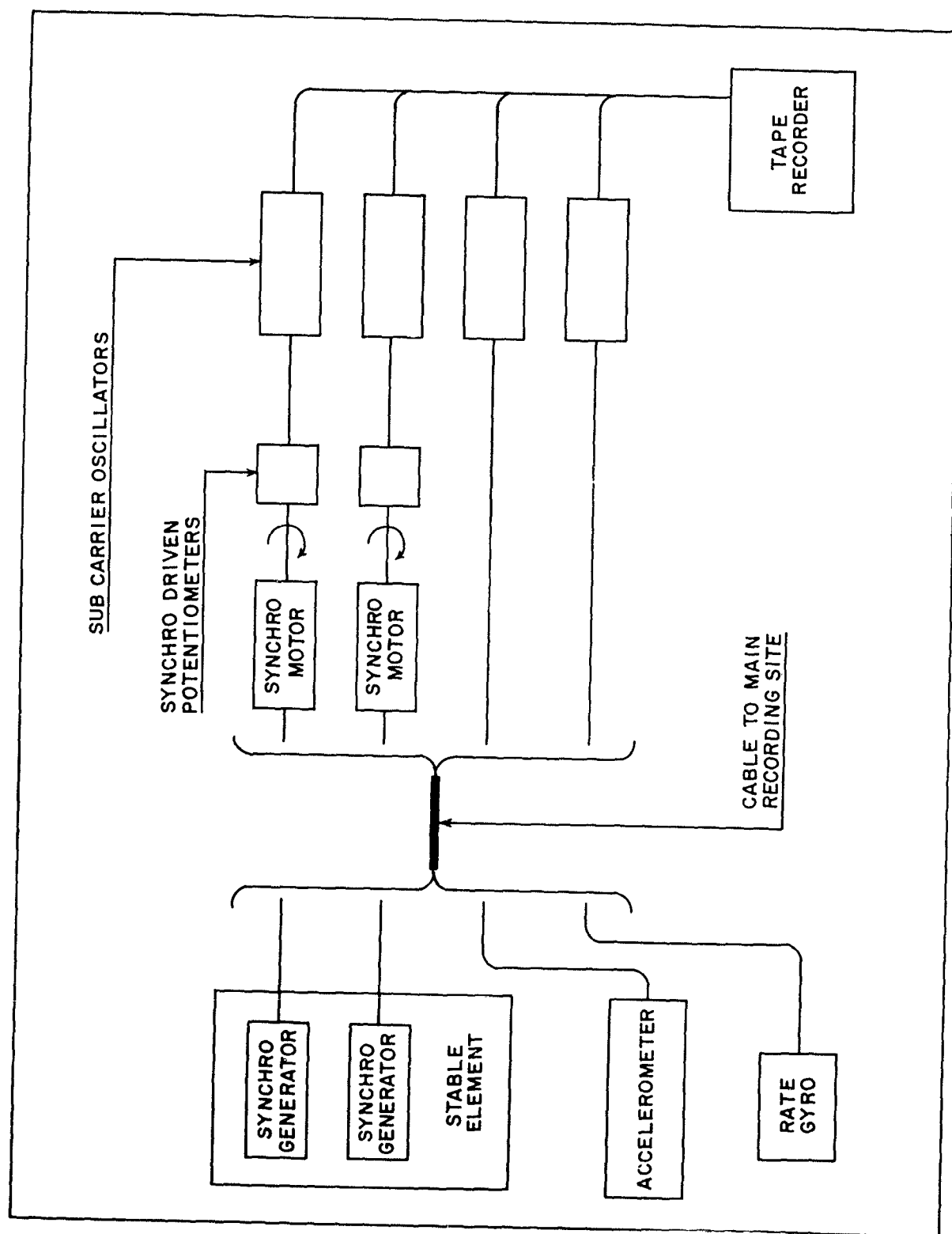


Figure 10. Block Diagram of a Typical Recording Installation

level rings. Synchro-motors located at the main recording site, and operating from the buses excited by these generators, are used to rotate the shafts of small potentiometers which have a fixed d-c voltage across them. The output from the rotating slide of each potentiometer is, therefore, a voltage that is proportional to the electrical output of the stable element and hence to the motion that is to be measured. This voltage is used to frequency-modulate a subcarrier oscillator. The outputs of several subcarrier oscillators of different frequency are combined and the resultant signal recorded on magnetic tape.

The two types of stable elements which will be most frequently encountered aboard aircraft carriers are the Mark 8 (Westinghouse) and Mark 6 (Arma). The former is used principally to stabilize the SP radar antenna, while the latter is used for fire control. The accompanying table (Table 1) lists the electrical and mechanical outputs of the various modifications for both types which are currently in service. The only outputs listed are level and cross-level. Other outputs, such as train order or deck tilt error, are occasionally available.

The level and cross-level outputs of a stable element are identically equal to pitch and roll respectively only when the axis of the stable element yoke — and hence the line of sight of the radar antenna, gun director, or other stabilized device — is aligned parallel to the fore and aft axis of the ship. If the stable device is trained to 090° or 270° relative, the level angle is not equal to the roll angle, as might be first thought, but differs by a small amount. Similarly there is a small difference between the cross-level angle and the pitch angle. This is because the bearings for the outer gimbal ring — the cross-level ring — are carried by the yoke which rotates as the stabilized device is trained. The axis of the cross-level ring is always parallel to the deck plane and the angle through which the outer ring rotates is measured in a plane normal to the deck plane. Pitch, however, is an angle lying in a vertical plane and hence cannot, generally, be measured by a rotation of the outer gimbal ring. The axis of the inner (level) ring is maintained horizontal; hence, the angle through which this ring rotates is measured in a vertical plane. Roll, however, is an angle lying in a plane normal to the deck and therefore cannot be measured by a rotation of the inner gimbal ring.

When a stable element is utilized as an information source for ship-motion recording, it is too much to expect that the recording group will have sole utilization. In by far the greater number of instances, arrangements must be made to share the instrument. Any rotation of the stable element yoke during recording periods will render the data valueless, however, and positive precautions must be taken to insure that if the yoke is rotated from the desired position, the recording party is made aware of it. This is not always simple, as frequently the

stabilized device is controllable from several different locations. There is no single solution to this problem and the recording group is forced to rely on its own ingenuity to devise some means whereby it is impossible for the yoke to be rotated without their knowledge. A further discussion of arrangements for stable element utilization is given in the section on shipboard organization in the appendix.

Table 1
Stable Element Characteristics

Mark 6

Level:	120 speed	Mechanical
Cross Level:	2 speed	Electrical
	72 speed	Electrical
	120 speed	Mechanical

Mark 6 - Mod 1

Level:	2 speed	Electrical
	36 speed	Electrical
	120 speed	Mechanical
Cross Level:	2 speed	Electrical
	72 speed	Electrical
	120 speed	Mechanical

Mark 8 - Mod 2

Level:	2 speed	Electrical
	36 speed	Electrical
*Cross Level	2 speed	Electrical
	36 speed	Electrical

Mark 8 - Model 4

Level:	2 speed	Electrical
	36 speed	Electrical
Cross Level:	2 speed	Electrical
	36 speed	Electrical

- * Mark 8 Mod 2, style 1282747 supplies 72 speed cross level in place of 36 speed cross level. A conversion kit is available to convert to 36 speed cross level.

Occasionally, it happens that the only convenient point at which access may be had to a synchro bus is at some point following a differential generator which introduces additional and, for the purpose of the recording group, spurious information. Care must be taken to avoid this when tapping into a synchro bus; if it is unavoidable, precautions must be taken to insure that no undesired information is introduced during the recording period.

In addition to the level and cross-level information supplied by the stable element, there is much additional information available aboard ship on synchrobuses. The ship's gyro provides yaw information which is transferred to gyro repeaters all over the ship on the one-speed and thirty-six speed own-ship-course buses. Wind velocity and direction are available from synchro buses and on the larger carriers even the closure speed of incoming aircraft may be obtained. The own-ship-speed buses transmit the velocity of the ship through the water as measured by the pitometer log.

It is imperative that a check of each synchro-circuit be made to determine the number and size of the synchro-motors it is supporting. Overloading a synchro-bus will seriously affect the accuracy of all the motors operating on that bus. There is further discussion of synchro accuracy and a table listing the maximum number of synchros of any size that may be operated from a generator of given size in the section of this report entitled "Accuracy".

If data are required other than those furnished by the sensing instruments normally carried aboard ship, additional instrumentation must be provided. This may include pressure indicators, strain gages, gyros, accelerometers, and so forth. Accelerometers should be roll-stabilized to keep orientation of the sensitive axis constant. For greater accuracy, pitch stabilization should also be used; but the error introduced by lack of pitch stabilization is small, as pitch angles rarely exceed 5° . There is further discussion of accelerometer accuracy in Section V of this report. Accelerometers, particularly in the after part of the ship, should be shock-mounted as a precaution against mechanical damage. The roll or pitch frequency of most ships is well below the natural frequency of commercial accelerometers, but the shaft vibrations (especially at full and flank speeds) are at frequencies that approach the natural resonant frequencies of some commercial accelerometers.

Angular rates may be obtained by differentiation of the level and cross-level angular displacements; however, it has proved generally preferable to employ rate gyros. In this respect a very good rule-of-thumb to adopt is never to obtain one quantity by differentiating another quantity if it is possible to make the measurement directly. For example, it is much more satisfactory to obtain acceleration through the

SECURITY INFORMATION—CONFIDENTIAL

use of an accelerometer rather than by differentiating velocity. This statement applies even more strongly to double integration or differentiation. In the course of analyzing the data in Section VII, it developed that observance of this rule-of-thumb was an absolute necessity.

The measurement of vertical displacements is an extremely difficult problem and will not be treated here. The subject is treated in an unpublished report, "Some Aspects of the Measurement of Vertical Displacement," by Martin R. Bates of the Bell Aircraft Corporation.

If gyroscopic instruments are supplied by the recording group as part of the instrumentation, they should be mounted well down in the ship and close to the point of minimum vertical acceleration. The accelerative forces encountered in rolling and pitching can have a serious effect on gyros which incorporate a pendulous erection mechanism. Gyros which do not have pendulous erection mechanisms may also be affected, for the forces affect the gyro through the suspension of the rotating member, while the inertial reaction is through the center of mass. Thus, unless the rotor is perfectly balanced, a couple is exerted which would cause precession.

There are numerous systems for recording the information obtained from the various sensing instruments, and the choice of which system to use depends largely on the form in which the records are desired, available equipment, and preferences of the recording group. If the proposed data reduction involves electronic analogue computation, magnetic tape recordings are probably the most convenient. Sub-carrier oscillators were used in the shipboard instrumentation covered by this report, frequency-modulated by the sensing-instrument outputs to record as many as eight channels per tape. More, however, could be used. Phase modulation could be as easily employed. Tape recorders should be selected on the basis of durability, dependability, and low wow and flutter. A constant-frequency drive to furnish accurate 60-cycle ac to the capstan motor is advantageous, as the line frequency of the ship power is liable to vary. It is also desirable to supply all a-c power to the installation through constant voltage transformers.

Every effort must be made to keep noise at a minimum. If existing spares are used in the remote cabling, they must be completely isolated from the remainder of the ship's interior communication system. A separate ground return should be run to each sensing instrument and the ship's hull should never be relied on as a ground. Difficulty has not been encountered during this project with noise on the 60-cycle power line, but this is an important source which should not be overlooked. Cables leading to remote instruments are very liable to pick up stray 60-cycle noise. As most of the frequencies encountered in ship motion occur well below this figure, filtering is not too difficult. It is prefer-

SECURITY INFORMATION—CONFIDENTIAL

able, on account of stray pick-up, and for simplicity, to operate the remote sensing instruments at maximum sensitivity at all times and adjust to the desired sensitivity by attenuating the signal at the recording station. As there will often be several sensing instruments of the same type, this reduces the number of current-carrying precision bleeders necessary; also, high voltage in the lines is maintained, thus keeping the percentage of noise as low as possible. As the signal is attenuated at the recording station, the stray noise picked up on the lines leading to and from the sensing instrument is also attenuated.

The illustrations accompanying Section VI show detailed views of the instruments mentioned in this section and photographs of a complete installation.

section V accuracy

In order to determine the over-all accuracy of the data acquired on a ship-motion recording trip, it is imperative that each element of both the recording and playback systems be critically examined. This will be done here, using the representative systems depicted in Figure 11, starting with the sensing devices and following through both systems until the motion is finally transcribed in graphic form.

The consensus of opinion, among people who have had considerable experience with stable elements in service in the fleet, is that the average unit will maintain an accuracy of ± 7 minutes during its service life. This figure represents an accuracy of $\pm 1\%$ for motions of about 12° . For smaller motions, the percentage is proportionally larger. If possible, the accuracy of the stable element should be checked prior to a recording trip, as the figure given is an average one and variations are to be expected in individual instances.

Suitable accelerometers have shown variations from an ideal, linear characteristic of as much as 7%. In all cases, the variations occurred at one end of the range, however, and the characteristic was considerably better near the center. Therefore there is a gain in accuracy when only a portion of the full range of the accelerometer is utilized. For the work on this project the estimated accuracy was $\pm 2\%$. Because the accelerometer characteristic is essentially linear over small portions of the curve, the resolution of the accelerometer is of greater interest than the linearity when recording small motions. Inherently, an accelerometer with a wire-wound resistance element cannot resolve two accelerations differing by an amount less than that represented by a half-turn. Typically, this may represent a few millig's. Accelerometers of the strain-gage type, having much better resolution, may be obtained. These offer one principal disadvantage; amplification is generally required as the output signal is on the order of a few millivolts.

The Ford Instrument Company states the accuracy limits for synchro-generators of their manufacture as ± 18 minutes. The figure for synchro-motors is ± 36 minutes for size 5. If a 36-speed synchro-system is employed, the input information is expanded so that 10° of ship motion results in 360° rotation of the synchro-generator and motor shafts. As the accuracy limits of the synchro-system remain unchanged, there is considerable gain in accuracy. Of course the gear train which has been inserted to achieve a 36-speed system introduces another possible source of error, but unless the gears are badly worn, this error is negligible.

It is important that the torque which a synchro-motor is required to deliver be as small as possible if accuracy is to be maintained. Potentiometers having very small torque requirements and a winding that is within $\pm 0.5\%$ of linearity are commercially available.

The d-c potential for the accelerometers and for the synchro-driven potentiometers should be obtained from a regulated source and should be carefully measured. With due care this voltage can be maintained within $\pm 1\%$.

Subcarrier oscillators are available which are linear to within $\pm 2\%$. This figure is determined by the variation from the straight line that best fits the curve of output frequency versus modulating voltage.

Typical tape recorders which are appropriate for this application have input-output characteristics which are linear to the extent that cross-modulation is less than one percent. If the speed of the magnetic tape as it passes under the recording head is not uniform, spurious frequency variations, termed wow and flutter, will be introduced into the recorded information. Wow and flutter are expressed as the percentage of all components between 0 and 300 cps occurring on playback of a tape recorded with a 3000 cps tone. A representative figure is 0.2% rms which indicates excursions of the 3000 cps signal of ± 6 cps. In a system employing frequency modulated oscillators the effect of wow and flutter is more pronounced, however. If the center frequency is 3000 cps and the band width is $\pm 7.5\%$ of the center frequency, or ± 225 cps, the wow and flutter would amount to $6/225 \approx 3\%$. Fortunately, the frequencies involved in ship motion do not occupy the entire range from 0 to 300 cps but lie principally below 10 cps. The wow and flutter components which are of importance are those lying in the range of the frequencies recorded, as others may be removed by filtering. In view of these facts, one percent appears to be a more realistic figure than three percent for the wow and flutter components.

The above remarks on wow and flutter presuppose that the tape is being pulled by a motor operating from an a-c source whose frequency

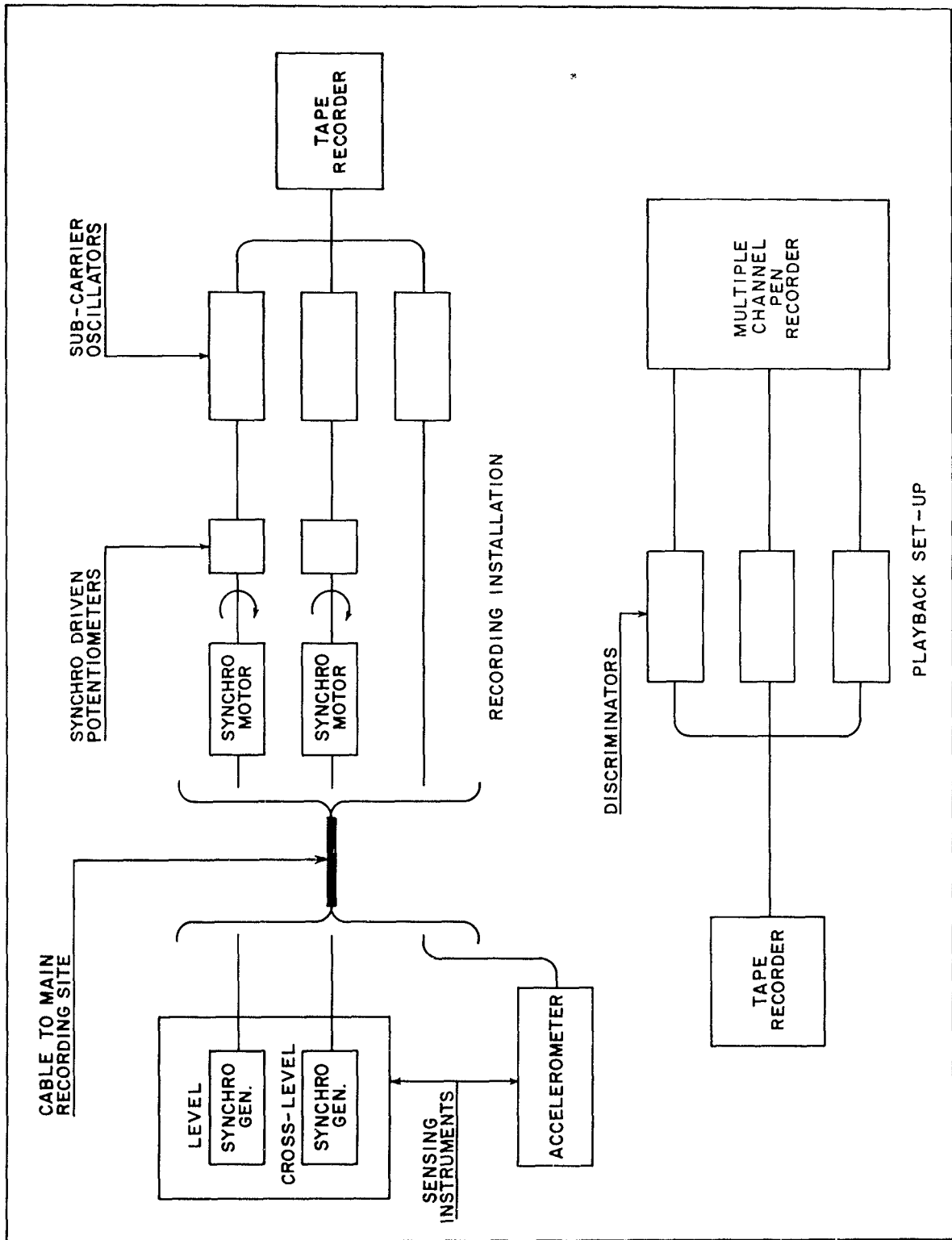


Figure 11. Representative Recording and Playback Equipment

SECURITY INFORMATION—CONFIDENTIAL

is constant. The frequency of the a-c supply aboard ship is liable to vary and a constant-frequency source is highly recommended. Some gyro-compass installations incorporate a controlled frequency source which may be utilized (with the ship's permission) if the power requirements are not too large. When such arrangements cannot be made, there are fork-drive units commercially available which will maintain a frequency accurate to five parts per million per degree centigrade.

The discussion of recorder linearity and the figures given, include the playback operation as well as the recording process.

The accuracy with which the amplitude-modulated signal obtained from a discriminator represents the frequency modulation of the input signal depends on how accurately the discriminator is balanced. Discriminators with a nominal accuracy of $\pm 0.5\%$ are available, but $\pm 1\%$ would probably be a more realistic figure, allowing for drift in both the discriminator and the subcarrier oscillator.

The final step in the playback process is the reduction of the data to graphic form and the inspection of the resulting motion record. There is a wide selection of devices for transcribing the information. Accuracy of 1% may be obtained on a graphic record that may be read to within $\pm 0.5\%$.

The figures which have been quoted in the preceding paragraphs are realistic ones, based on actual experience, but the accuracies represented are not arrived at without considerable care. In the following paragraphs some of the precautions which must be observed to achieve and maintain accuracy are indicated.

A gyro maintains a fixed direction in space rather than with respect to the earth. The vertical-reference gyro of a stable element located at the equator would therefore appear to make one complete revolution every 24 hours about an axis parallel to the polar axis, if some corrective means were not employed. Usually the correction is applied as a small torque, varying from zero at the poles to a maximum at the equator, which causes a precession just sufficient to maintain the spin axis of the gyro vertical despite the rotation of the earth. On the Mark 8 stable element the latitude correction is a very simple adjustment which may be made by a member of the recording group. Adjustment of the latitude correction mechanism on the Mark 6 should not ordinarily be attempted. The group should insure that the proper adjustment is made by the designated members of ship's company, however, as an improper setting will have a serious effect on the recorded data.

SECURITY INFORMATION—CONFIDENTIAL

Synchro systems maintain the specified accuracy only when properly used. Table 2 lists the number of synchro-motors which may be operated from a synchro-generator. If a larger number of motors than that listed in the Table is operated from one generator, the accuracy of the entire system will decrease sharply.

The torque which a synchro-motor develops at any instant varies directly with the angular separation of the motor and generator shafts.

Table 2

Synchro Motor and Generator Characteristics

Generator		Maximum Number of Motors Accurately Driven		
Size		1F	3F	5F
1		1	—	—
3		3	1	—
5		4	3	2
6		18	12	9
7		36	24	18

Motor	Accuracy Limits	Torque Gradient	Rotor Inertia
Size	Maximum Minutes	oz-in. per degree from synchronism	oz-in. ²
1F	90	0.085	0.55
3F	36	0.260	8.28
5F	36	0.470	7.80

Generator	Accuracy Limits	*Torque Gradient	Rotor Inertia
Size	Maximum Minutes	oz-in. per degree from synchronism	oz-in. ²
1G	18	0.085	0.34
3G	18	0.260	1.15
5G	18	0.470	2.96
6G	18	1.460	10.41
7G	18	3.600	31.7

*Generator Used as Motor

Thus the torque which the motor is capable of delivering to the load becomes smaller as the position of synchronism is approached. If the load requires a high torque, the motor may stop while there is still an appreciable angle between the position of the motor shaft and the position of synchronism. Under these conditions, the generator will attempt to relieve the system unbalance by rotating the device to which it is coupled until the generator shaft is positioned with the motor shaft. As instruments such as stable elements and gyro compasses are delicately balanced, there is an excellent chance that the generator will be able to cause enough rotation to create serious trouble. There are two preventive measures for this situation. First, the load on each synchro-motor should be kept to an absolute minimum; second, an amplifier should be used to isolate each synchro-generator from the motor it drives.

Stabilization of accelerometers was briefly mentioned in the preceding section, but will be treated with considerably more detail here. The range of an accelerometer is commonly given by the manufacturer for horizontal mounting. If the accelerometer is used to record vertical accelerations, an allowance must be made for gravity. Thus an accelerometer with a nominal range of 0 to +2 g may be used to record vertical accelerations of -1 to +1 g. If the ship takes a 10° roll, the gravity bias on the instrument instead of amounting to 1 g will be $1 \times \cos 10^\circ = 0.985$ g, an error of 0.015 g. An additional error is introduced because the axis along which the acceleration is measured does not coincide with the true vertical. This error is also a cosine function. If the true vertical acceleration is, say 0.2 g, the error is $0.2 \cos 10^\circ = 0.197$ g, an error of 0.003 g. Thus the total error in measuring a 0.2 g vertical acceleration during a 10° roll is 0.018 g, a discrepancy of almost 10%. As both errors are always of the same polarity, they are always additive. Furthermore, they are always cumulative on integration of the data, effectively prohibiting the possibility of obtaining velocity or displacement information from the data record of unstabilized accelerometers.

The preceding remarks on achieving and maintaining accuracy apply for the most part to situations which cannot be corrected by accurate calibration. One notable exception is that certain stable elements, among them the Mark 6, Model 1, are provided with means of manually introducing roll and pitch angles. This permits inclusion of the roll and pitch synchro-circuits in the calibration.

Nonlinearities in the remainder of the recording equipment may be corrected by accurate calibration. The number of calibrating voltages applied to the subcarrier oscillator inputs depends on the accuracy of calibration that is desired. It was considered adequate for the work performed on this project to use three voltages — ± 2.5 volts and 0.

SECURITY INFORMATION—CONFIDENTIAL

These three voltages provide markers at the edges of each channel and at the center.

Wow and flutter cannot be corrected by calibration since they are not constant. These effects are inherent in the design and construction of the recorder. Frequency variation of the a-c power supplied to the Capstan motor produces the same effect as wow and flutter but is not referred to in this way since it does not originate in the recorder. It may be corrected by operating the capstan motor from a controlled frequency source.

There are two principal methods of overcoming wow and flutter. The first of these, of course, is to select a recorder in which these qualities are minimized by good design and construction. The second method consists of recording, in addition to the motion signals, the signal from a constant-frequency source, such as a stable one kc oscillator. This signal is played back through a discriminator of the proper frequency to obtain an amplitude-modulated signal. Any amplitude variations are the direct result of flutter and wow and are identical to the variations introduced into the information records. To remove the effects of flutter and wow from the information it is necessary only to subtract the output of the one kc discriminator from the output of each of the other discriminators. The source of the one kc signal must have high stability or the system is worthless.

Over-all accuracy of two percent is normally considered very good for field work. Higher accuracy, in general, may be attained only with the expenditure of disproportionate amounts of time and money. This discussion of accuracy has been made with this factor in mind. The intention has not been to present a complete discussion of all the factors affecting the over-all accuracy of a motion recording installation, but rather to give a brief outline of the principal sources of inaccuracy and indicate some of the methods which may be used to compensate and correct.

section VI typical installation

At this time Bell Aircraft Corporation has made motion-recording installations of varying complexity on seven aircraft carriers. The most recent and most successful of these was made aboard the U.S.S. Oriskany, for her trip around Cape Horn from Guantanamo, Cuba, to San Diego, California, during the summer of 1952. This was the first time, incidentally, that an aircraft carrier had ever rounded Cape Horn.

Sufficient advance notice of the trip was received to permit careful planning, building and testing equipment, calibrating instruments and making one preliminary trip. Adequate time intervened between the preliminary trip and the long voyage to permit revisions and the addition of new equipment.

It might seem, with such preparation, that once under way the accumulation of motion records would be a simple matter of pulling a few switches. Nothing could be further from the truth. Many difficulties were encountered and the fact that excellent motion records were brought back is evidence of a great deal of hard work after the voyage commenced. Those who are planning similar trips would do well to take note of the troubles encountered and remember that these mishaps are only typical instances of thousands of possible difficulties.

The block diagram, Figures 12 and 13 show the interconnection of units in the installation. In the next few paragraphs a brief description of the equipment as a whole will be given, following which a more detailed discussion of some aspects of the installation and the operation will be presented.

The installation was straight-forward, although its completeness tends to make it appear highly complicated. A Mark 8 Model 4 stable element supplied pitch and roll data. Yaw information was obtained from the 36 speed own-ship-course bus. Four accelerometers were

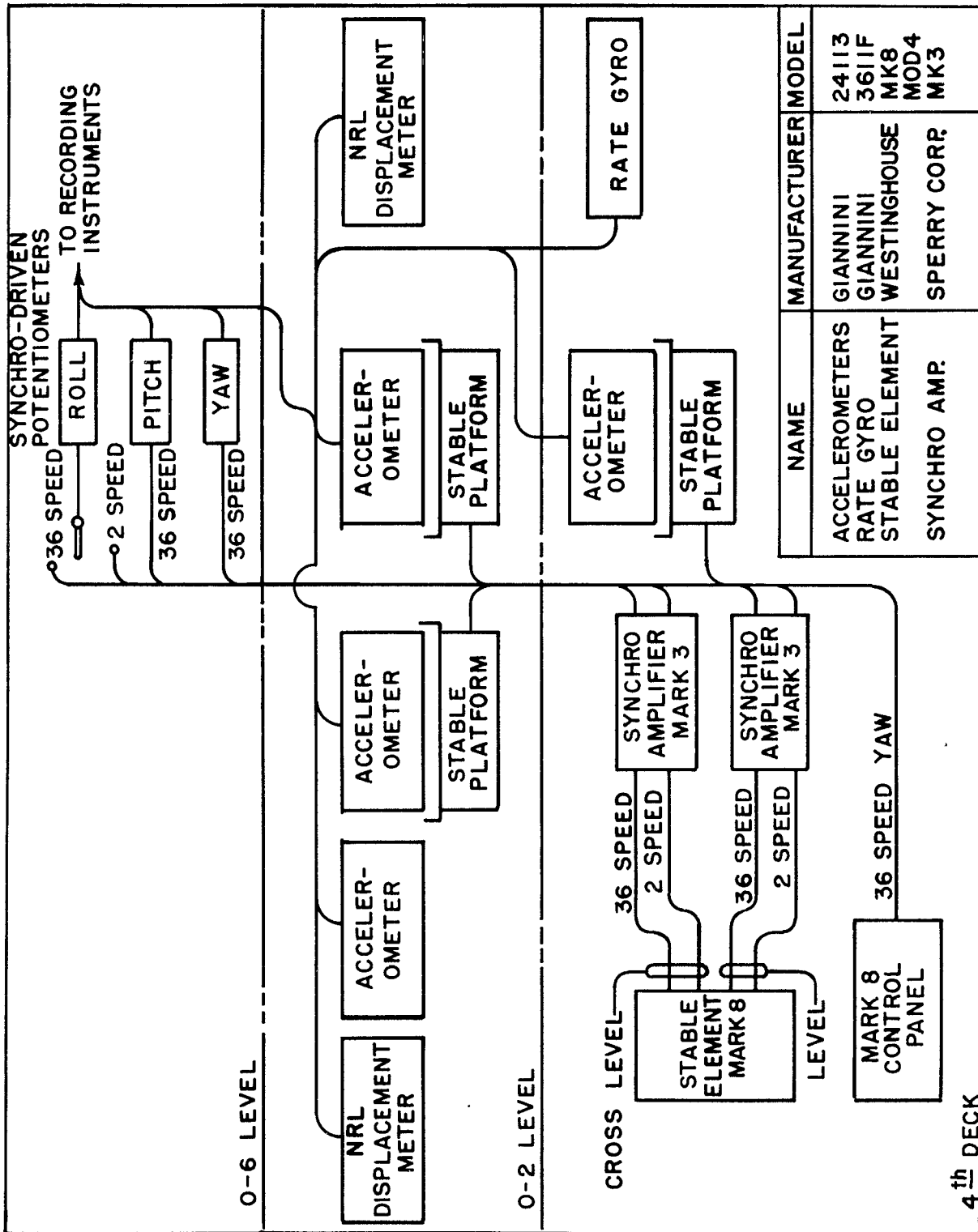


Figure 12. Sensing Instruments — USS Oriskany Installation

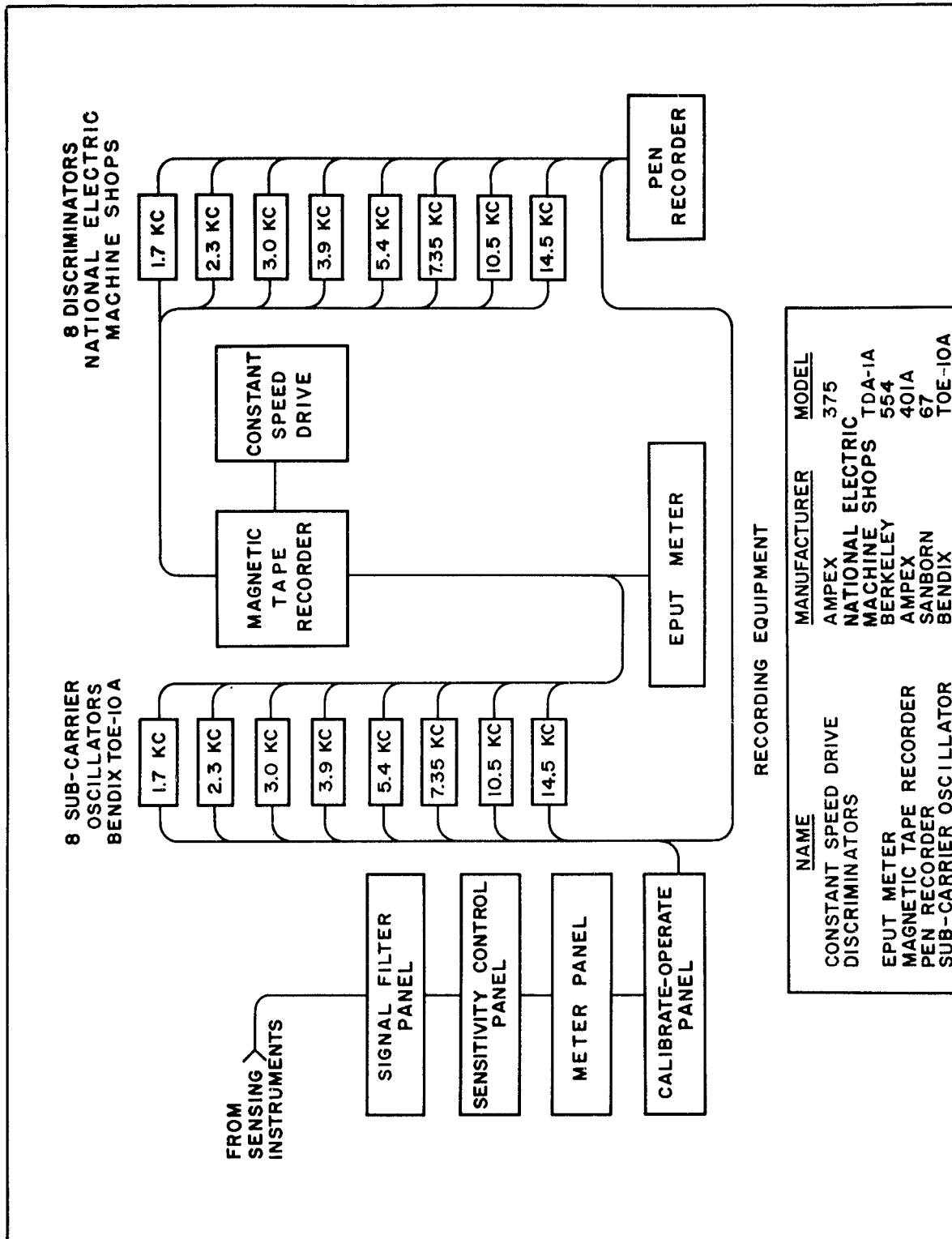


Figure 13. Recording Instruments — USS Oriskany Installation

used, three of which were mounted on one-axis stable tables. A rate gyro and two displacement meters (the latter furnished by the Naval Research Laboratory) completed the sensing instruments used for electrical recordings. A Minneapolis-Honeywell vertical gyro furnished by the David Taylor Model Basin was not used for electrical recordings as the output was too low. A few graphical records for comparison with the Mark 8 were made however.

The recording site chosen was on the 0-6 level in the SPN/12 compartment. This location was convenient for observing flight operations and permitted maximum utilization of existing spare cables. Two-speed and 36-speed level and cross-level buses, and the 36-speed own-ship-course bus were run to the recording site. The cables carrying the output signals of all sensing instruments were also carried to this point. All signals were filtered by 14 cps low-pass filters. These filters were added after the preliminary trip during which the noise level was measured. The lines from all sensing instruments were run to the signal filter panel where the desired signals were selected by patch cords.

All instruments except the Minneapolis-Honeywell gyro were operated at maximum sensitivity at all times for the reasons noted in the section on Accuracy. The Sensitivity Control Panel carried the attenuators necessary to keep the signals within the limits of ± 2.5 volts required by the subcarrier oscillators. The meter panel associated with the sensitivity control panel provided continuous monitoring of the output signals from the sensing instruments.

By means of the single-wafer switch on the Calibrate-Operate Panel, calibration voltages of -2.5, 0, or +2.5 volts could be applied to all channels simultaneously. This panel also carried jacks for the pen-recorder input plugs, facilitating graphical recording directly from the sensing instruments.

The subcarrier oscillator panel carried, in addition to the eight subcarrier oscillators, two voltage-regulator tubes and associated dropping-resistors for the oscillator-plate voltages. Pin jacks were provided on this panel for connection of the Events-Per-Unit-Time (EPUT) meter.

The outputs of the subcarrier oscillators were combined and the resulting composite signal recorded. Eight discriminators were connected to the recorder playback amplifier to provide continuous monitoring of the recorded information during the recording process. A patch panel, mounted in the center of the discriminator rack, permitted the four channels of the pen recorder to be connected to any four of the

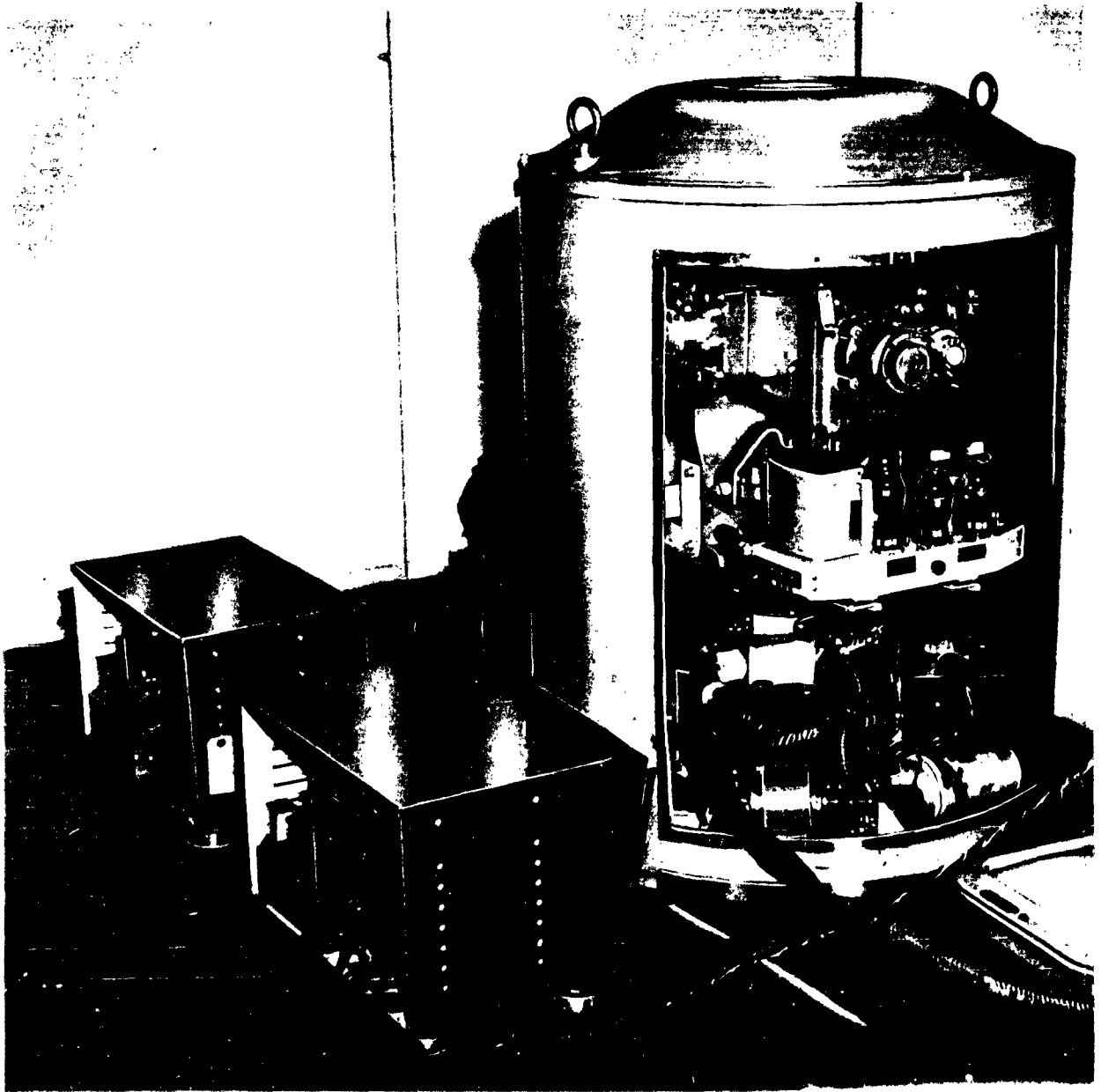


Figure 14. Stable Element — USS Oriskany Installation

discriminators. Thus graphical records could be obtained during either recording or playback. By use of the jacks on the calibrate-operate panel, it was possible to connect one channel of the pen-recorder to the signal input of one of the subcarrier oscillators, and an adjacent channel to the output of the corresponding discriminator. Nonlinearities or noise originating in the intervening equipment would thus be immediately apparent upon visual comparison of the pen traces.

The preceding paragraphs have presented a general outline of the installation. A more detailed discussion of some phases of the installation follows:

One notable feature of this trip was that the recording group had sole utilization of the stable element which had been installed in anticipation of the future arrival of SPN/6 equipment and for possible use by the SPN/8. The stable element had been modified to allow the yoke to be locked on 0° relative bearing; pitch, and roll were then identically equal to level and cross level, respectively, and no difficulty was experienced from rotation of the yoke during recording periods.

The Mark 8 Model 4 stable element is normally equipped with control transformers in the level and cross-level output circuits. It was necessary to replace these with synchro-generators. The 5G synchros in the level circuits could have supplied adequate power for recording purposes, as the only load applied was the 5F synchro used to drive the microtorque potentiometer. Nevertheless, an amplifier was used for isolation purposes to prevent any possibility of load reflection back to the stable element. The 5G synchros in the cross-level circuits were required to operate four 5F motors, including the three associated with the accelerometer stable tables. The amplifier was necessary, therefore, because of both power requirements and isolation. The synchro-amplifiers were modified Sperry Mark 3 amplifiers. Originally intended to operate on a combined 1-speed, 36-speed system, as used with gyro compasses, they were redesigned to operate on a combined 2-speed, 36-speed system.

The three one-axis stable tables were constructed especially for this trip. Each one was built from the gyro gimbaling system of a discarded A-5 autopilot. Stabilization achieved was not as good as had been anticipated, although it was estimated to be within half a degree for the amidships table. It is believed that a greater error existed in the fore and aft tables due to twisting of the ship which appeared as an additional error in stabilization.

A total of seven power supplies was incorporated in the installation. These included the two constant-frequency supplies for the tape recorders, three identical 200-300 volt supplies, and two low-voltage

INSTRUMENTS IN PROGRESS

IN CASE OF EMERGENCY
NOTIFY E-R DIV DUTY OFFICER
OR BELL AIRCRAFT REPRESENTATIVE

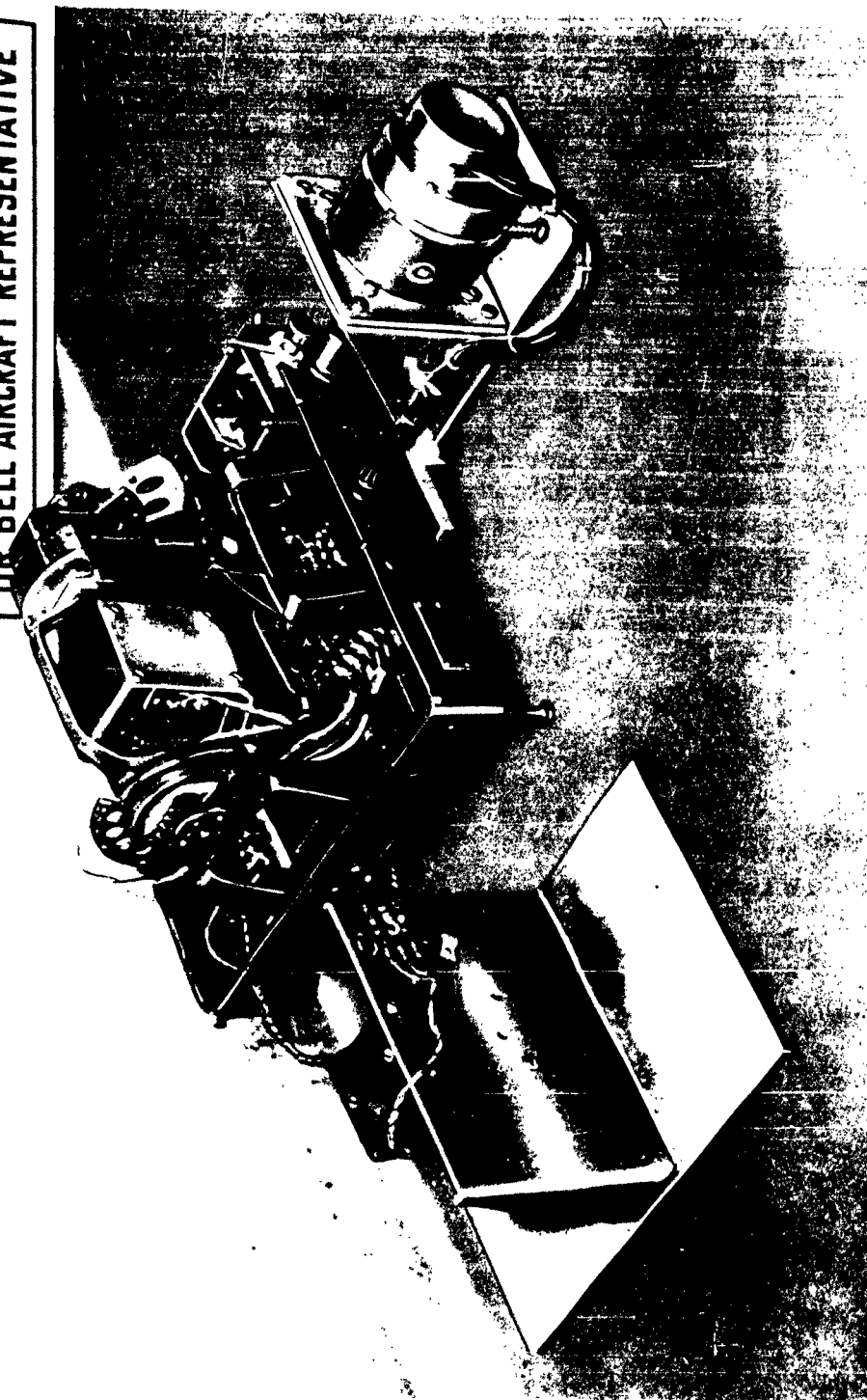


Figure 15. Accelerometers Mounted on Unstabilized Mount (left) and One-Axis Stable Table (right)

SECURITY INFORMATION—CONFIDENTIAL

supplies. Two of the 200-300 volt supplies were used to furnish ± 15 volts dc to the recording instruments, as well as the ± 2.5 volts dc calibration signal; the third supplied the plate voltage for the subcarrier oscillators. The subcarrier oscillator filament power was furnished by a low-voltage supply which was adjusted to six volts. The second low-voltage supply furnished power for the rate gyro. All ac except the primary excitation for the synchro-circuits was drawn from two constant-voltage transformers operating from the ship's 110 volt, 60 cycle supply. No difficulties due to variations in either supply voltage or frequency were experienced.

The installation was made while the ship was at Bayonne, New Jersey, by Bell Aircraft Corporation engineers and technicians, Navy yard personnel, and members of ship's company. The preliminary trip from Bayonne to Norfolk, although beset by calm seas, served to provide an opportunity for testing of the installation. As a result of these tests, it was deemed advisable to filter all information signals due to the high noise level — approximately .8 volt composed principally of 60 cycle. It was also decided to change the resistance in the sensitivity control circuits at this time, in order to obtain more accurate quantitative data. The recording group left the ship at Norfolk and returned to the Bell Aircraft Corporation laboratories to construct the new equipment.

About a month later, the group rejoined the ship at Guantanamo for the voyage to San Diego, California, by way of Cape Horn. Within two days the equipment revisions had been completed and no further difficulties occurred except those which are to be normally expected on such a trip. These are enumerated below.

Seven discriminator failures were experienced at various times. On two occasions the EPUT meter failed, one failure requiring several hours' work to locate and to correct. The rate-gyro power supply gave continual trouble which was particularly annoying as the gyro and supply were located in the stable element room, four decks down, while the recording site was on the 0-6 level, six decks up. After repeated trips up and down the intervening ladders, the rate gyro and power supply were brought up to the main recording site whereupon the power supply failed completely, and was replaced by batteries. It developed on recalibration after the voyage was completed, that the rate gyro had not been balanced for mounting in the position in which it was used, and no recordings of pitch rate were used in the data analyses.

Although the recording group had unrestricted use of the stable element, the power to the stable element was interrupted on several occasions as part of the damage control problems at which the crew

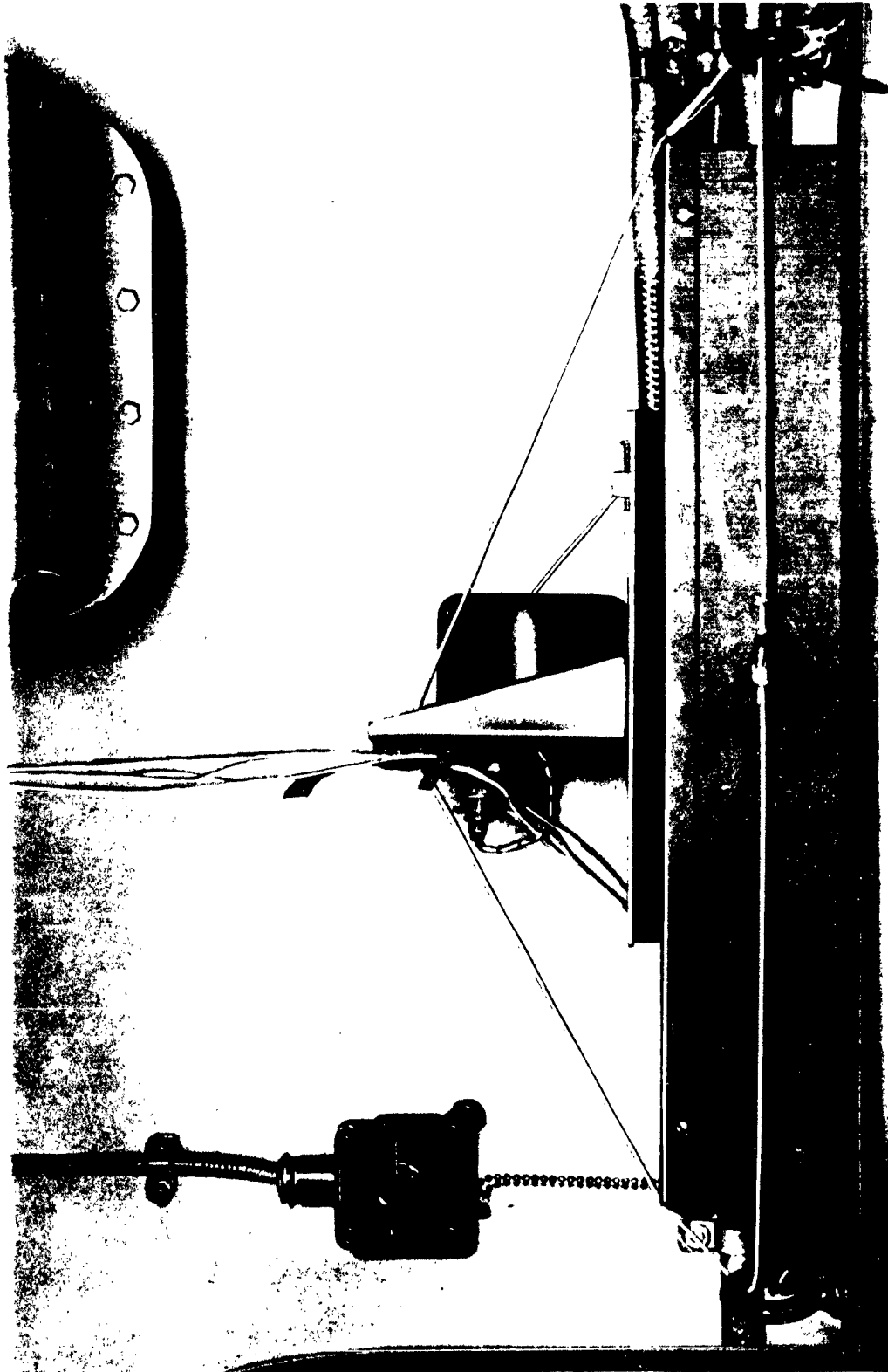


Figure 16. Rate Gyro and Mount

exercised while under way. The power interruption caused the vertical reference gyro to tumble with the result that the stable element had to be checked frequently to ascertain that the vertical reference was properly erected.

The tape recorders caused little trouble, although a recorder failure and a capstan-drive amplifier failure were both experienced. Noise in the playback amplifiers caused considerable alarm, until it was determined that the noise came from the amplifier and not from the tape.

Just after rounding Cape Horn a severe storm was encountered and both Secondary Con and Radio 5 were flooded. All cabling and wiring in both compartments had to be replaced, and the accelerometer and stable table in Secondary Con were damaged beyond possibility of repair on board. Fortunately, spare accelerometers had been brought along. Almost simultaneously with this near catastrophe, one of the synchros failed and one of the synchro-driven potentiometers developed an intermittent open.

No seasickness was experienced by members of the group and other personnel casualties were limited to the shellback initiation and one broken arm.

For the benefit of those who are planning a motion-recording trip the equipment list is included as Table 3. This list includes spares but does not include labor cost on equipment constructed by Bell Aircraft Corporation, nor the cost of equipment which was borrowed.

The labor involved in the trip amounted to approximately 3,000 manhours, almost equally divided between engineers and technicians. The time spent at sea is included in this figure on the basis of 40 hours a week. The time is computed to the termination of the voyage and does not include any time spent in data reduction or analyses.

SECURITY INFORMATION—CONFIDENTIAL

Table 3
Equipment List

2	Ampex Model 401A Magnetic Tape Recorders at \$1,000	\$2,000
24	Bendix TOE-10A Subcarrier Oscillators at \$150	3,600
9	National Electric Machine Shops Type TDA-1A Discriminators at \$500	4,500
1	Berkeley Model 554 EPUT meter	750
9	General Electric Company 5F synchros at \$60 (obtained on surplus)	540
8	Giannini Type 9 microtorque potentiometers at \$60	480
9	Giannini Model 24113 Accelerometers at \$355	3,195
1	Giannini Model 3611F Rate Gyro	520
1	Sanborn Model 67 4-channel Pen recorder	3,000
1	Budd Addarack CR-1779 Cabinet	65
3	Lambda 28C Power Supplies at \$150	450
2	Sola Type 30808 Constant Voltage Transformer at \$80	160
2	Ampex Model 375 Fork Driven Capstan Amplifier (ruggedized) at \$750	1,500
1	Hewlett-Packard Model 410B Vacuum Tube Voltmeter	245
144	Rolls Magnetic Recording Tape at \$9 a roll	1,396

Built by Bell Aircraft Corporation

Calibrate-Operate Panel	
Meter Panel	
Signal Filter Panel	
Sensitivity Control Panel	
Subcarrier Oscillator Mounting Panel	1,500
Voltage Adjust Panel	
Discriminator Connection panel	

Miscellaneous Spare Tubes	\$ 550
---------------------------	--------

Miscellaneous component spares, resistors, condensers, etc.	\$ 550
---	--------

TOTAL	\$25,001
-------	----------

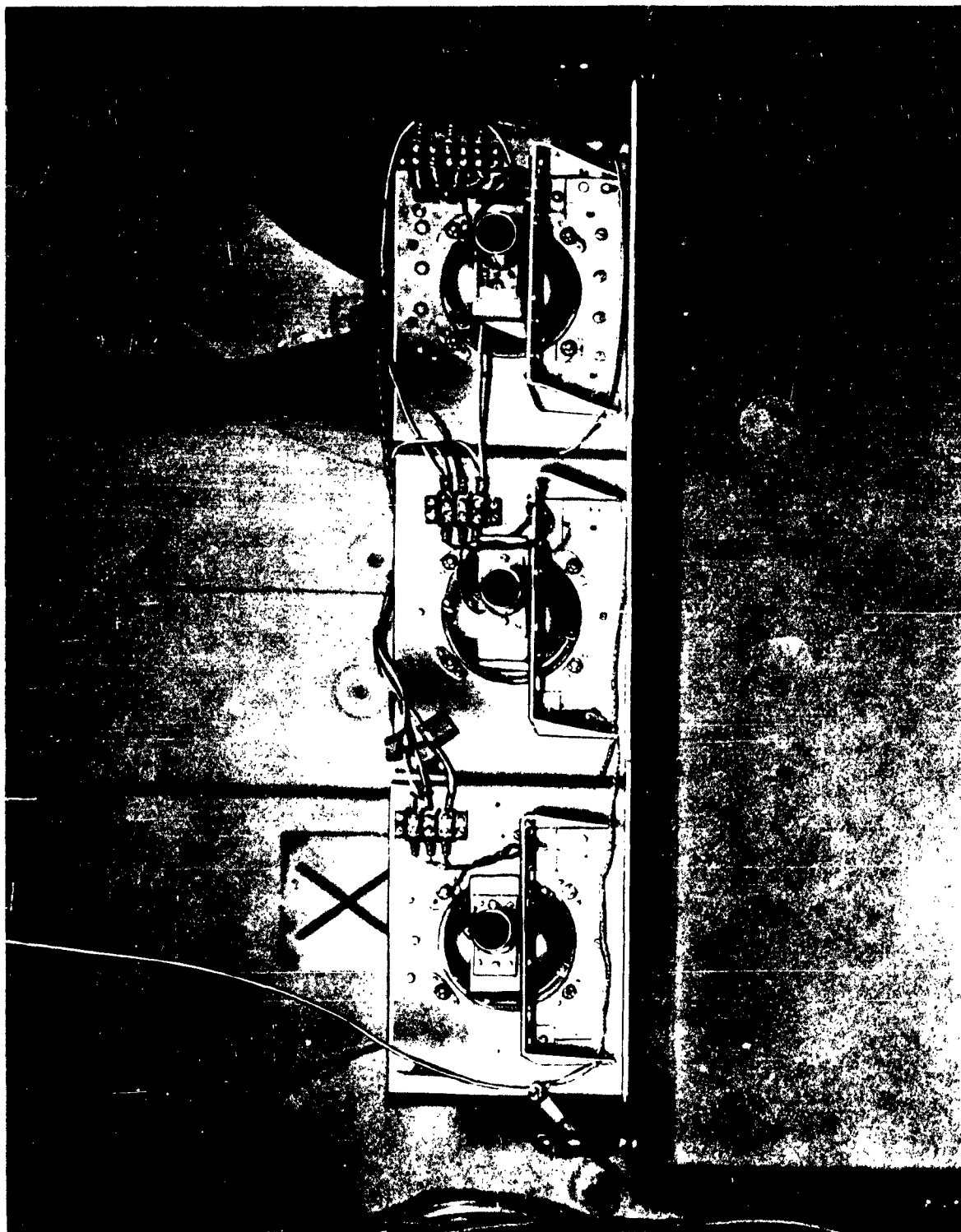


Figure 17. Synchro-Driven Potentiometers

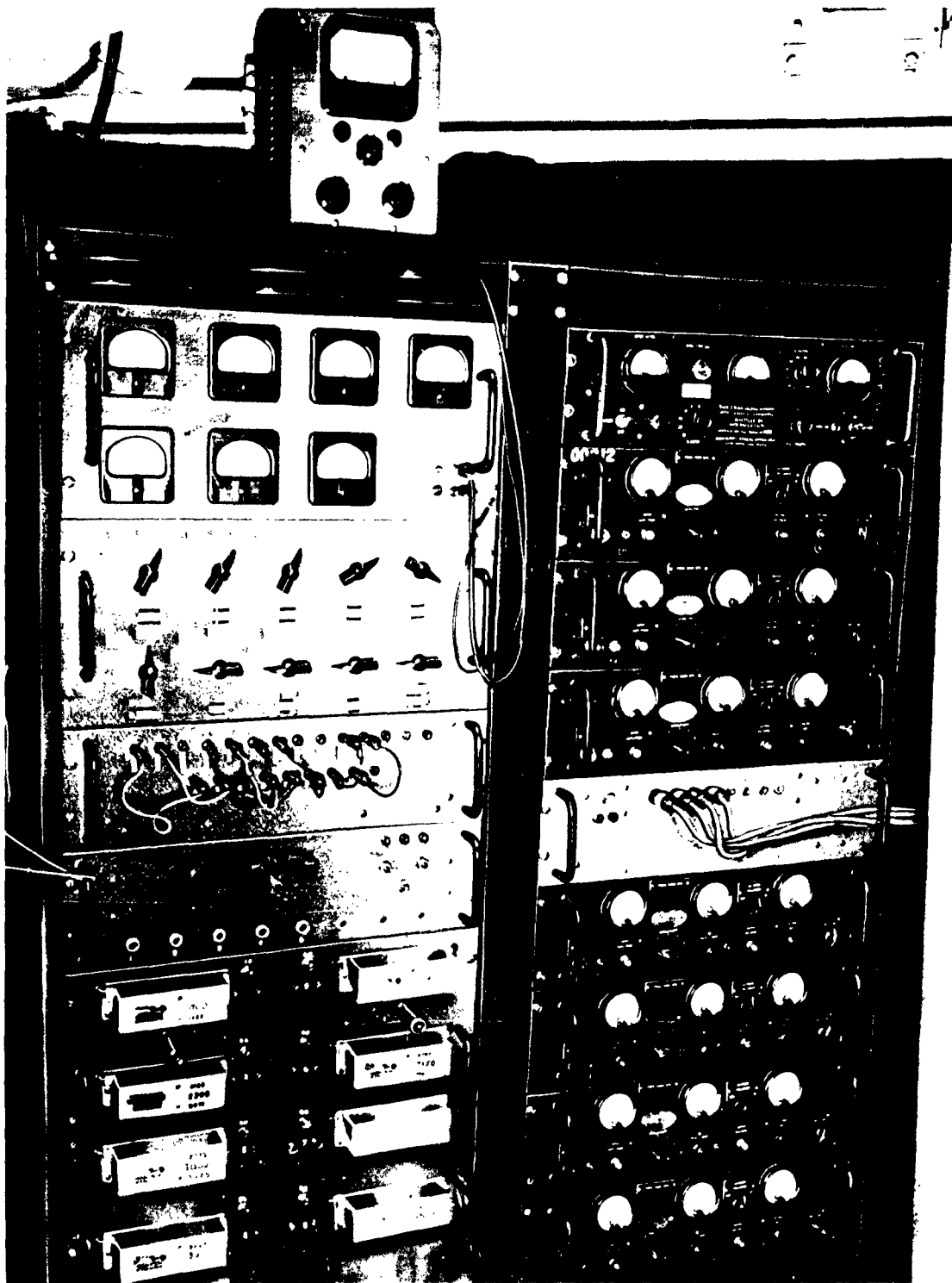


Figure 18. Equipment Racks at Main Recording Site

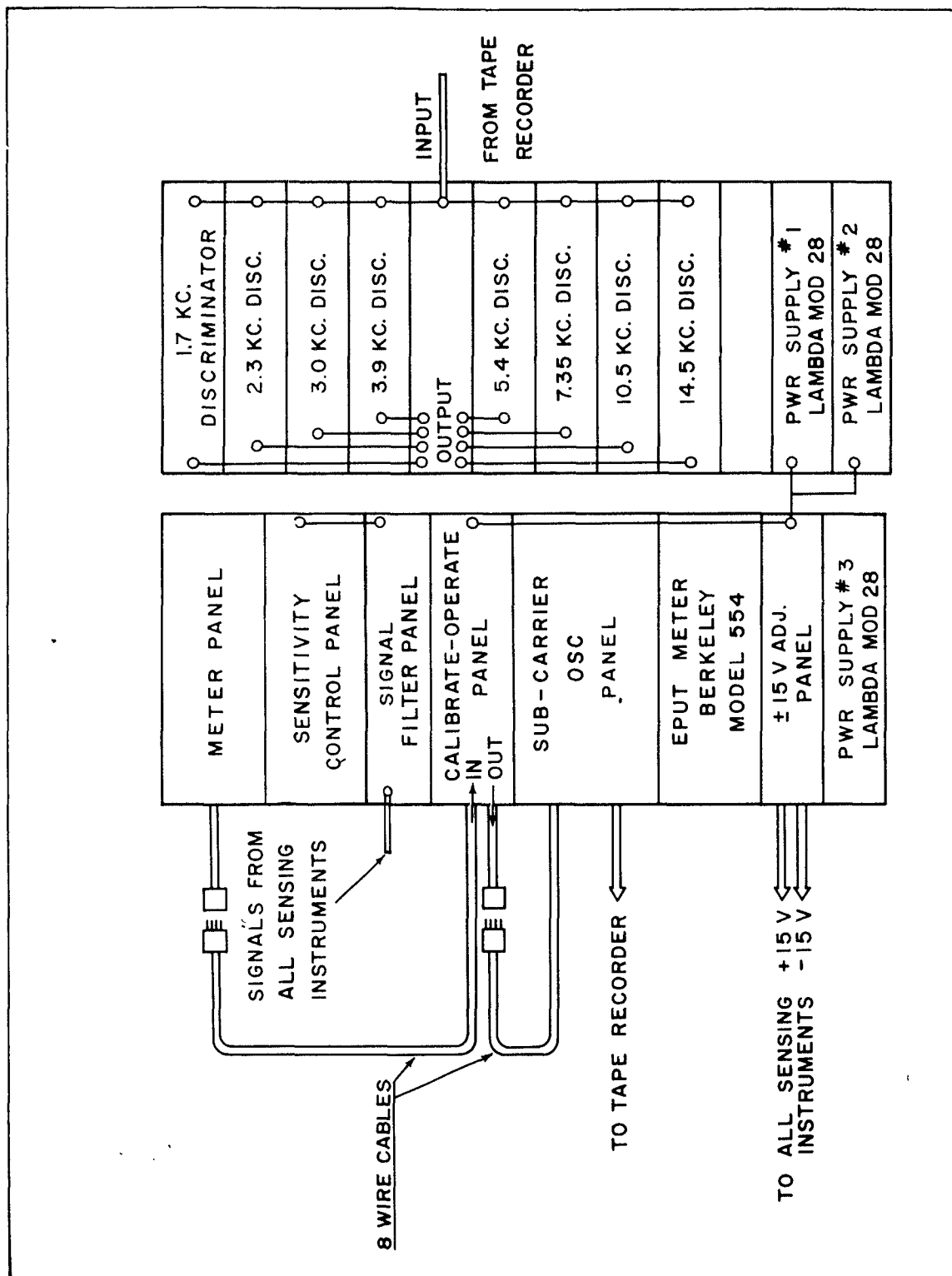


Figure 19. Rack-Mounted Equipment at Main Recording Site

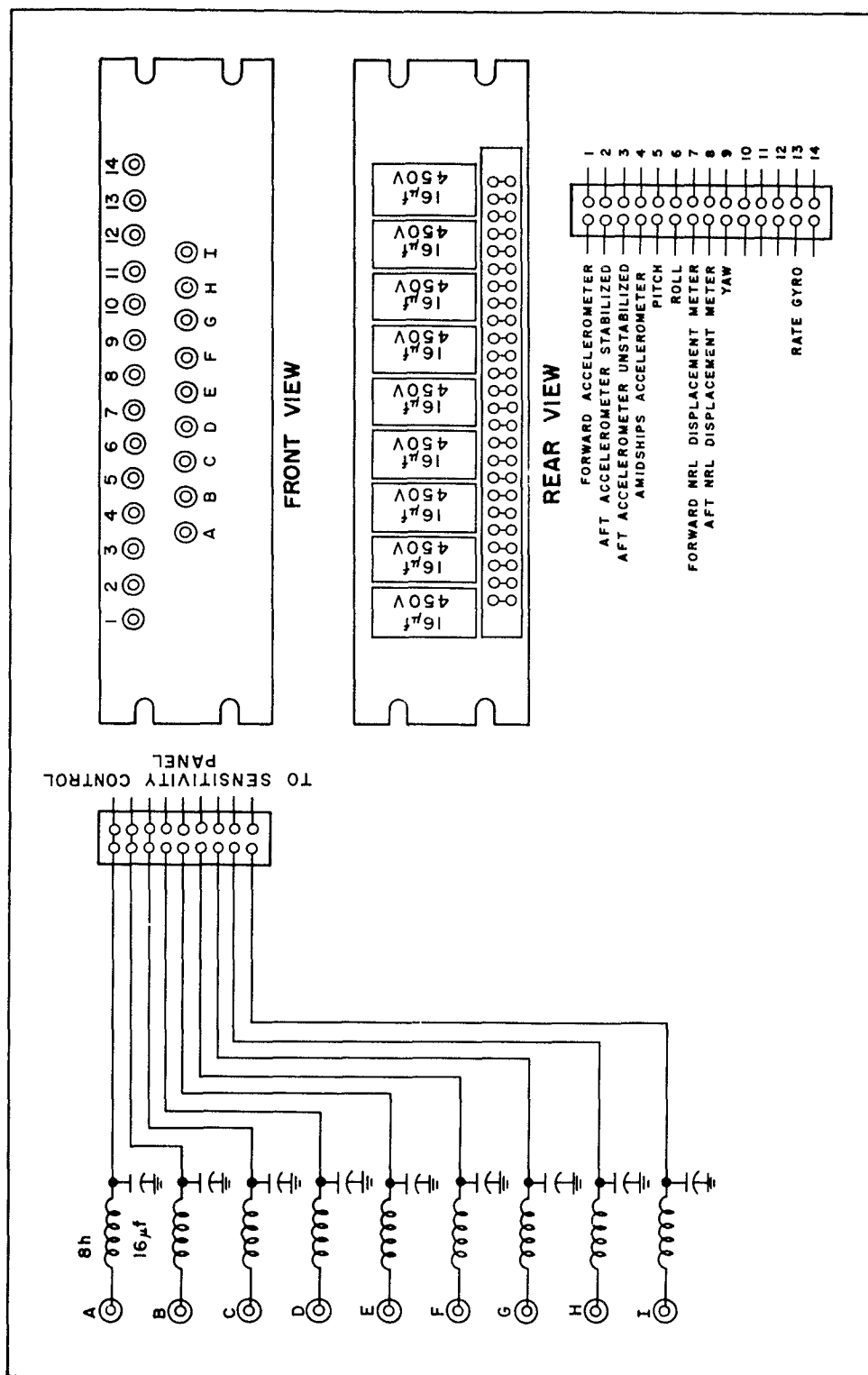


Figure 20. Signal Filter Panel

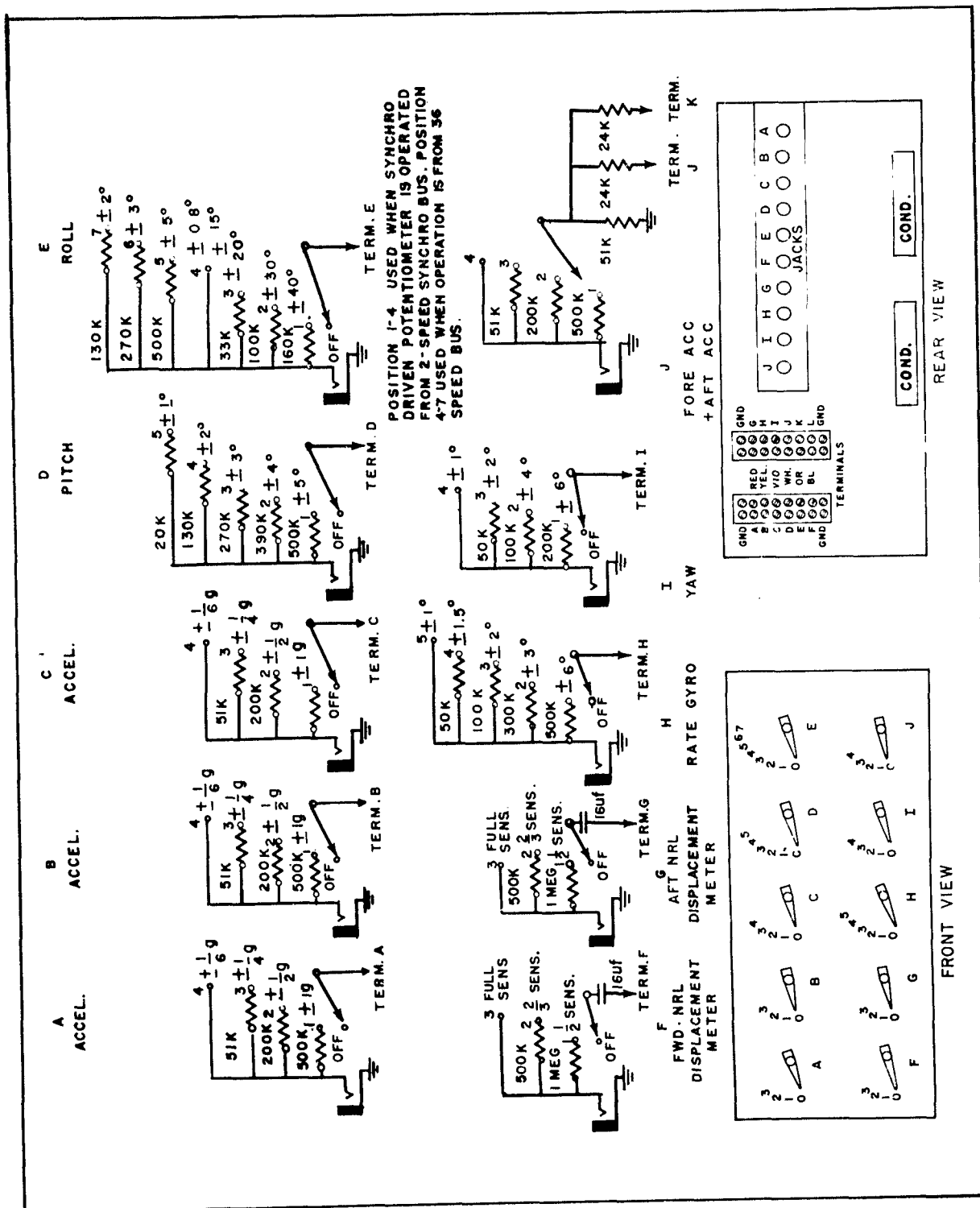


Figure 21. Sensitivity Control Panel

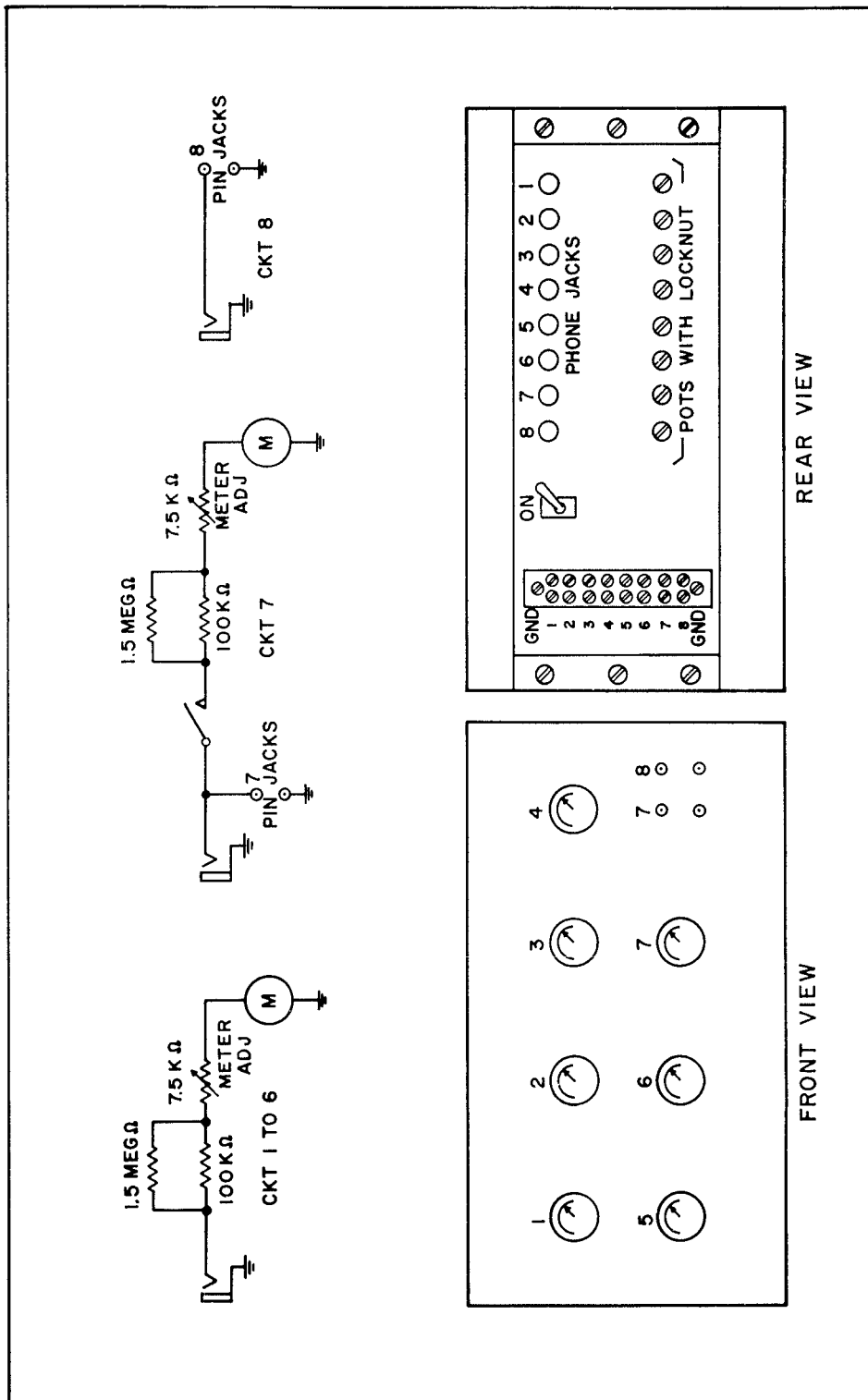


Figure 22. Meter Panel

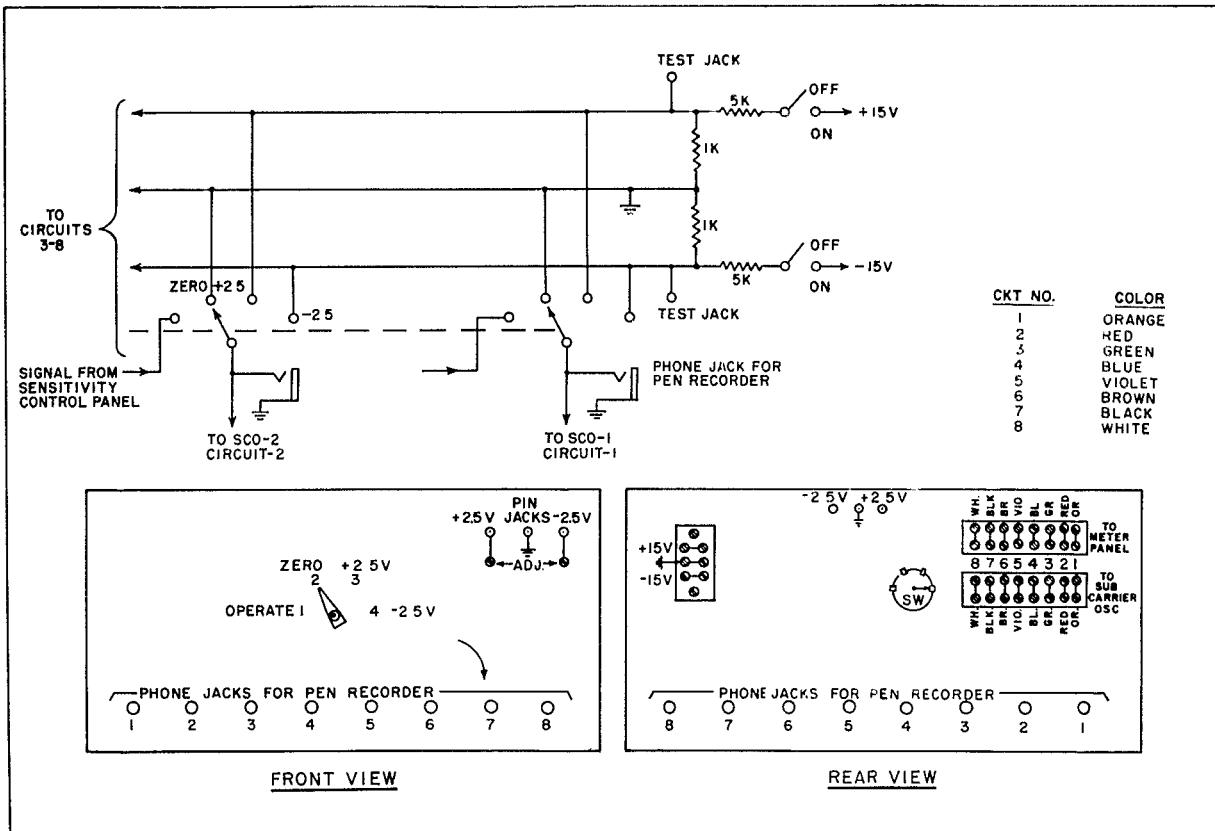


Figure 23. Calibrate-Operate Panel

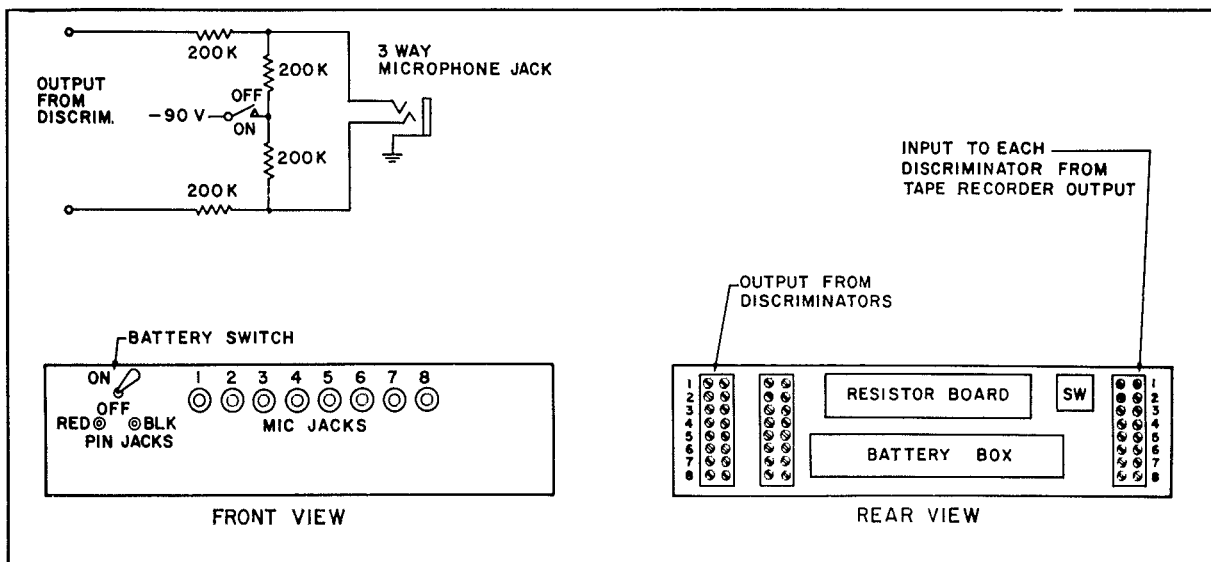


Figure 24. Discriminator Connection Panel

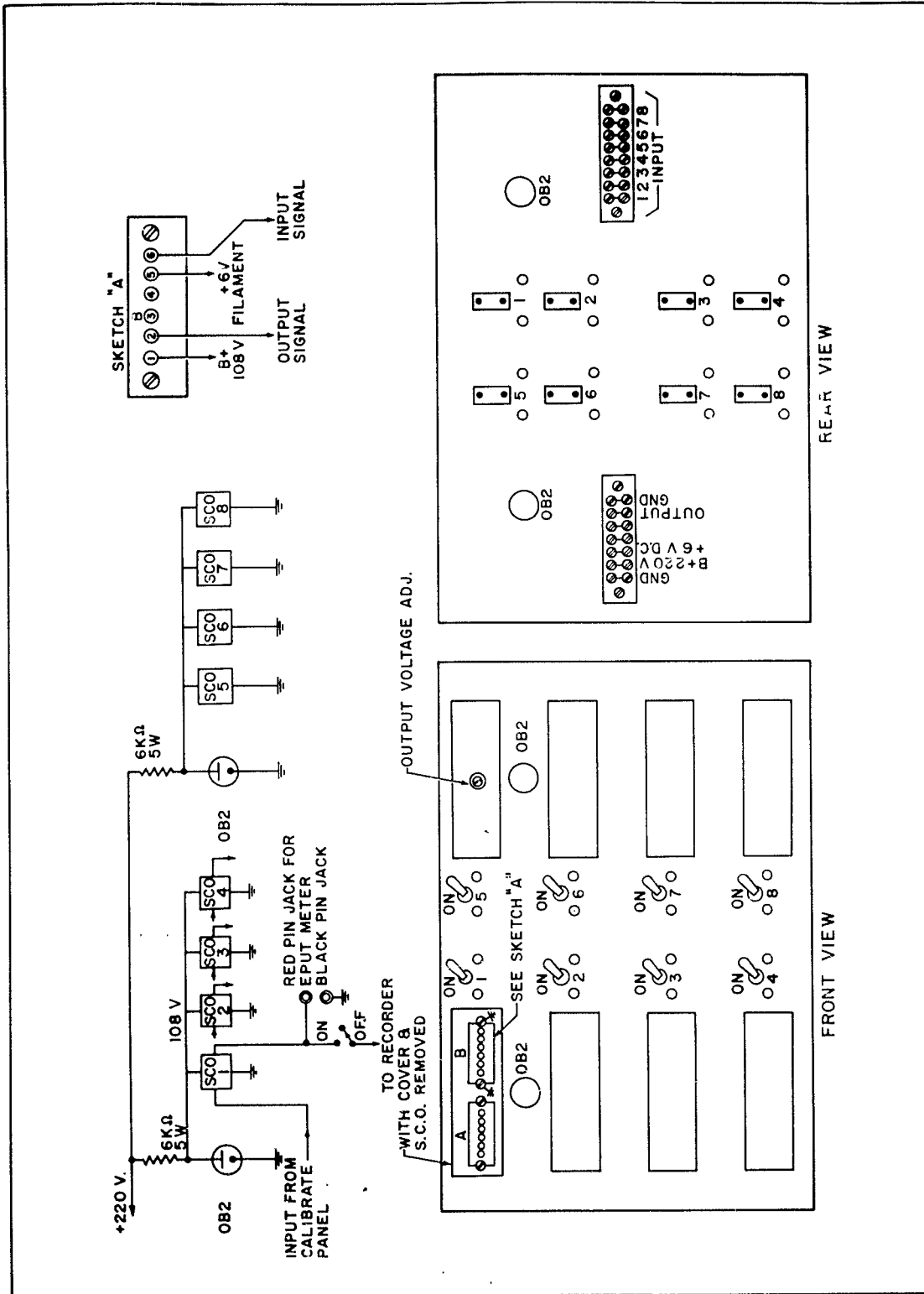


Figure 25. Sub-Carrier Oscillator Mounting Panel

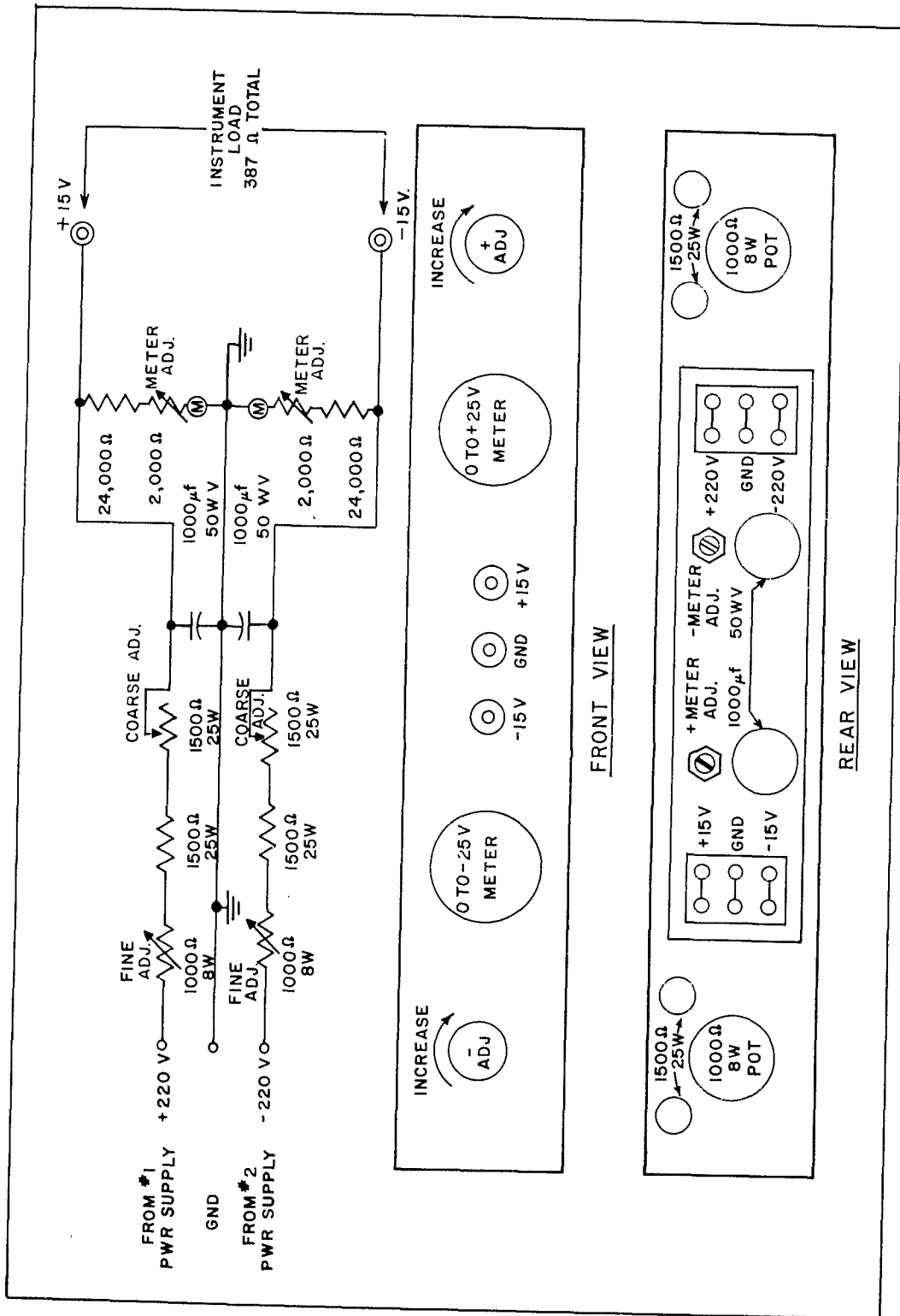


Figure 26. Voltage Adjustment Panel

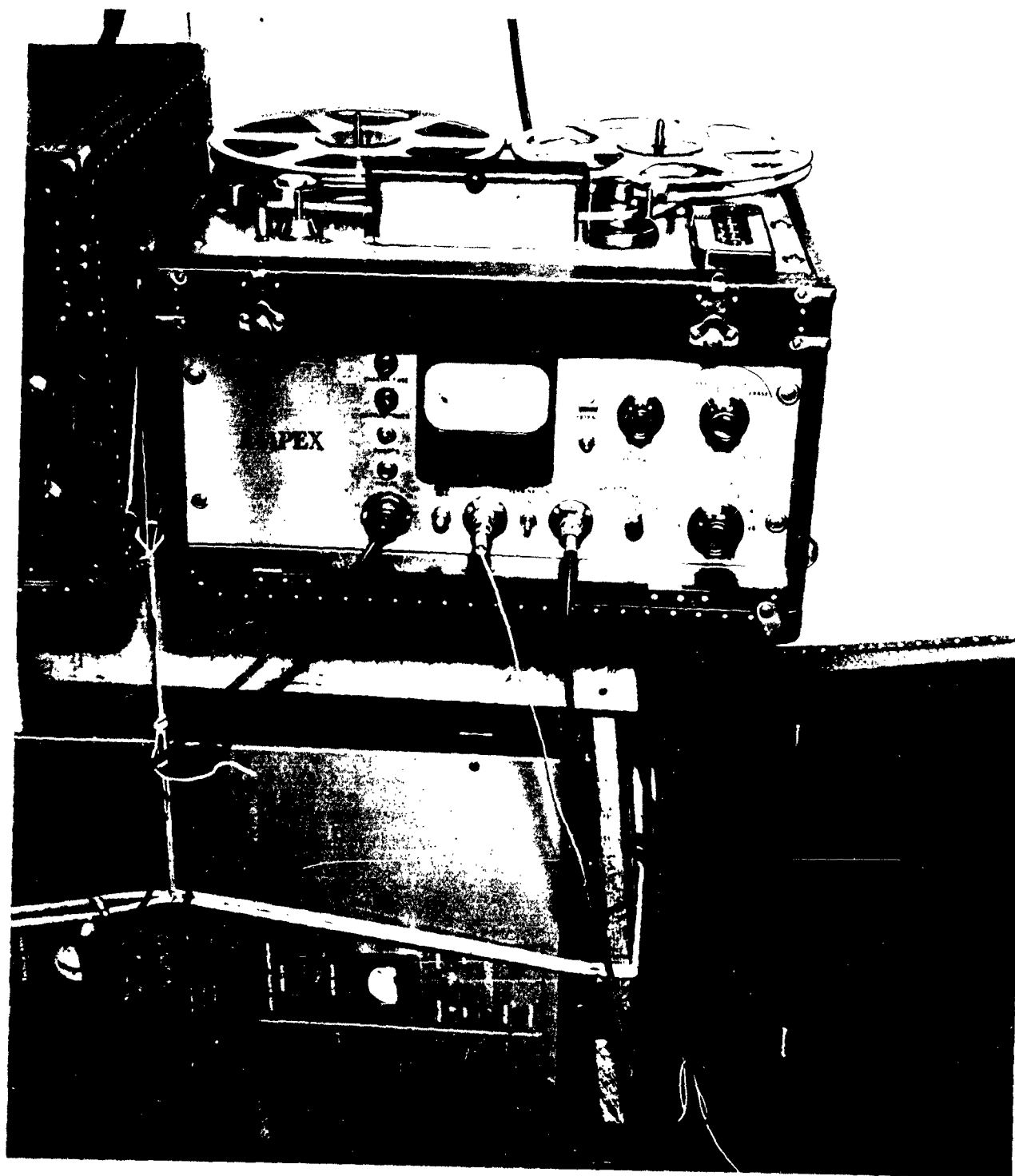


Figure 27. Tape Recorder and Constant-Frequency Capstan-Drive Amplifiers

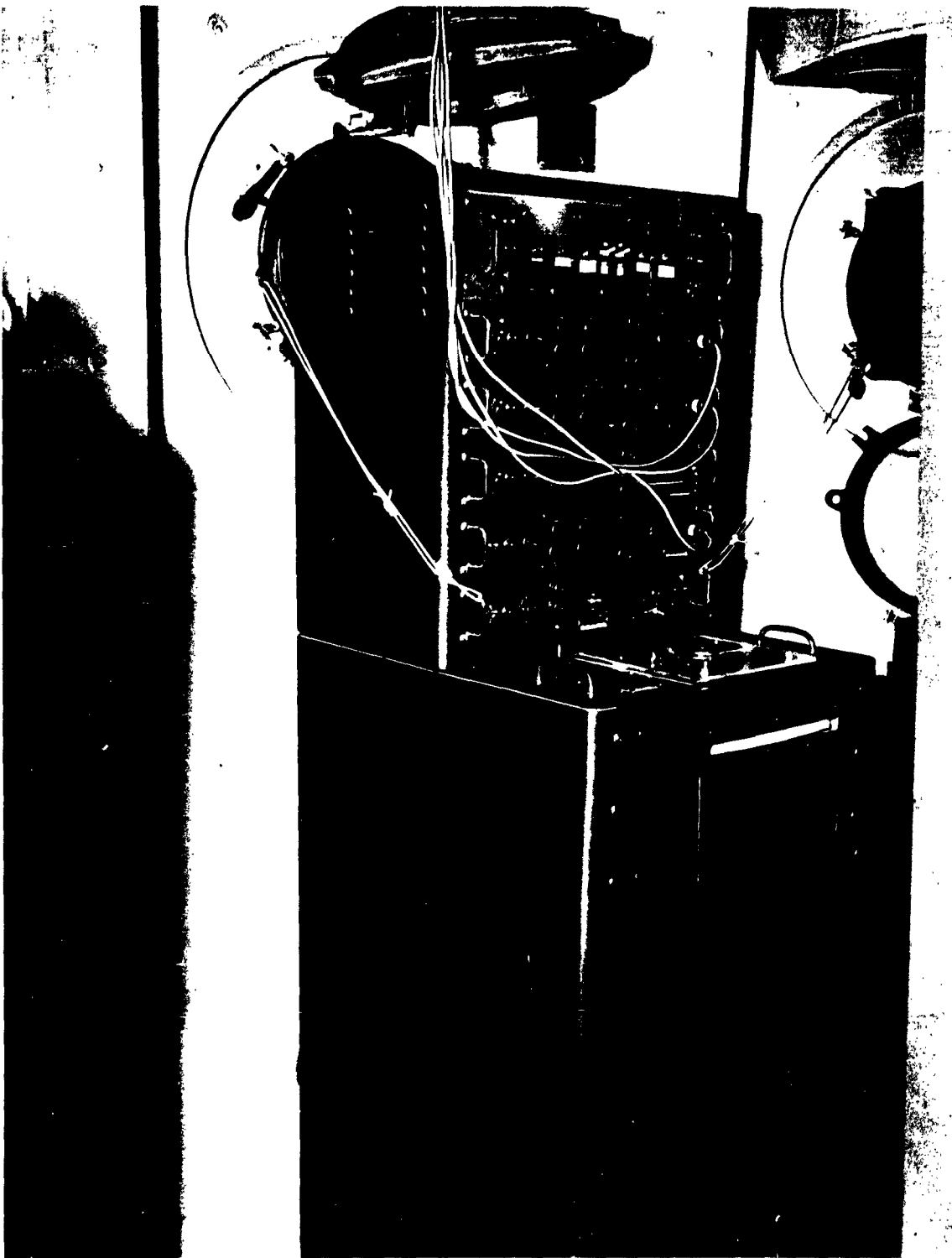


Figure 28. Sanborn Four-Channel Pen Recorder

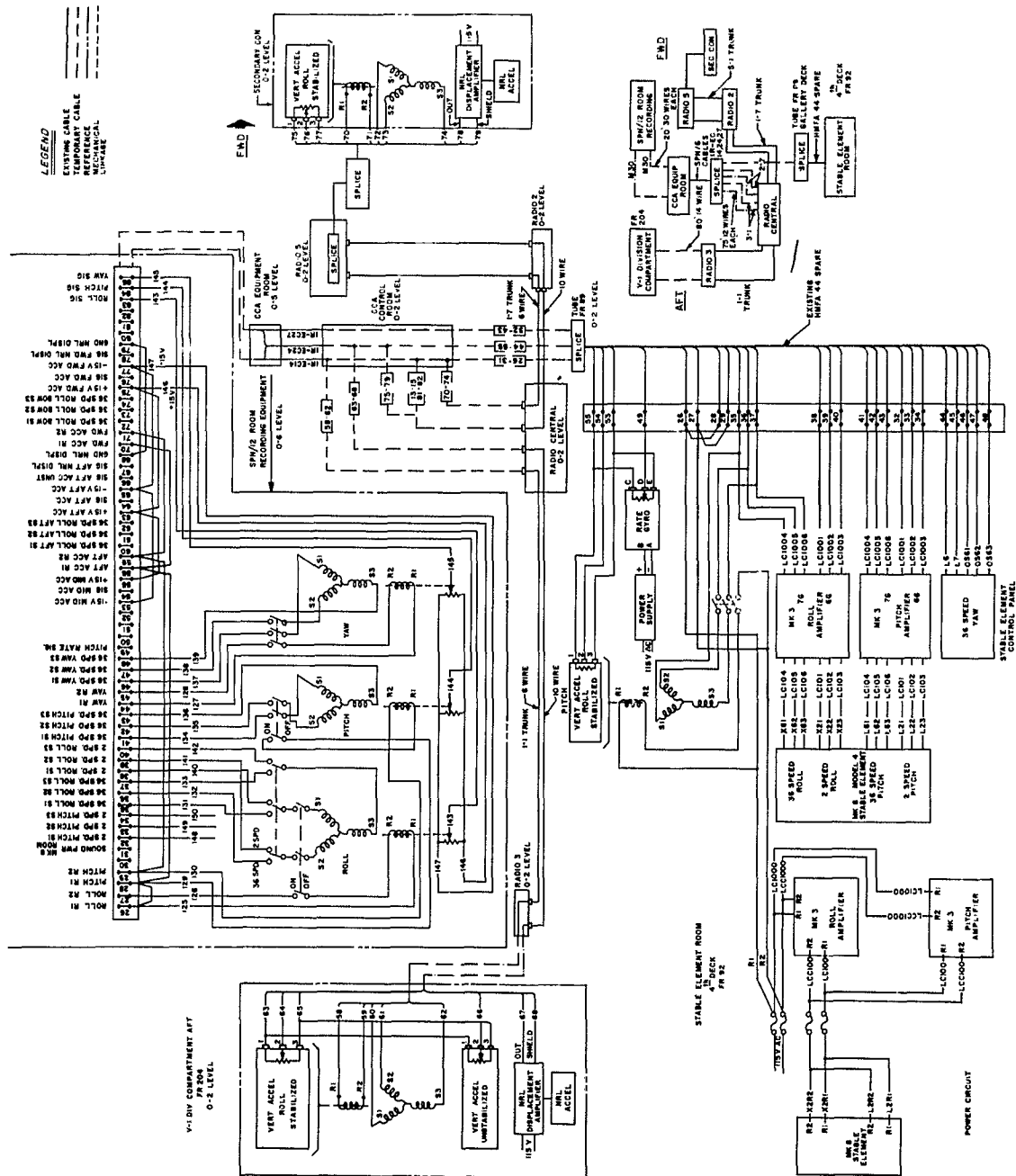


Figure 29. Cabling Diagram - USS Oriskany Installation

section VII data analysis I

The objectives of this program were to obtain answers to certain questions pertaining to the predictability of ship motion: Is prediction possible over sufficiently long intervals and with sufficient accuracy to be a practical solution to the deck-motion phase of the carrier-landing problem? If so, will one predictor design suffice for all ships and all sea conditions? As mentioned in the introduction, there existed two logical paths which might be followed; either one leading to an understanding of the motion. Before entering into a detailed discussion of data-reduction methods it seems advisable to review briefly the two alternatives and the reasons on which the choice was based.

The first approach is to consider the ship as a mechanical transducer having a transfer function which relates the motion of the ship to the surface disturbance of the ocean. From an electrical engineering point of view, the ship may be regarded as a filter which operates on the input to form the output. If the characteristics of any two of the three components of this simple system were known, the input, the filter, and the output, the characteristics of the third could be found.

The second alternative is to study the motion itself and to attempt to establish the necessary prediction criteria by direct analysis.

Although the first alternative was not overlooked, it appeared to present several disadvantages at the time a decision had to be made as to the method on which the greater effort would be applied. No detailed information was available concerning the nature of the forcing function -- i.e., the surface disturbance. The problem of obtaining an accurate transfer function of a ship appeared to be a considerable one, and no method was foreseen for obtaining the prediction criteria from the solution of the system.

On the other hand, Wiener and others had already developed techniques for obtaining prediction criteria for a stationary time series

based on the past history of the series itself. It seemed simpler to follow the more conservative approach of applying existing theory to data records, and it was decided that this line of investigation would be the principal one followed. The remainder of this section is limited to discussion of the methods and results of data reduction carried out in accordance with this choice. In the sections following this one, it will be shown how the data analysis, performed within the framework of the second alternative, led to an eventual consideration of the first.

One of the existing methods of determining the predictability of a time series required knowledge of the autocorrelation function; therefore, the method of obtaining this function, and its significance, is treated first. The amplitude spectrum and its relation to prediction criteria is considered next.

As the name implies, the autocorrelation function is constructed by a quantitative comparison of every part of a sample of data with every other part. A plot of the autocorrelation of a highly cyclic phenomenon exhibits an oscillatory curve with a gradually decaying envelope. The fact that the decay is gradual implies good predictability. If the phenomenon is less cyclic, a more rapid decay of the envelope is evident and the possibility of prediction is poorer. In either case, the cyclic nature of the data might not be apparent upon inspection of a graphic sample. As might be expected, the autocorrelation of either a sine or cosine, two perfectly predictable functions, is a cosine curve having a constant envelope.

The autocorrelation is not useful in determining the predictability unless the time series representing the data is stationary. This means that the character of a sample taken over any finite interval must be independent of the location of the interval.

Mathematically, the autocorrelation may be expressed by:

$$\phi(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^{+T} f(t) f(t+\tau) dt$$

Where $f(t)$ is the time series which is to be autocorrelated, $2T$ is the length of the sample over which the autocorrelation is to be taken, and τ is the time displacement between the two parts of the data. Although the theory demands that T range from negative to positive infinity, in practice it is limited by considerations other than the practical impossibility of attaining infinity. If the ship changes course or speed, or if the surface condition varies, $f(t)$ can no longer

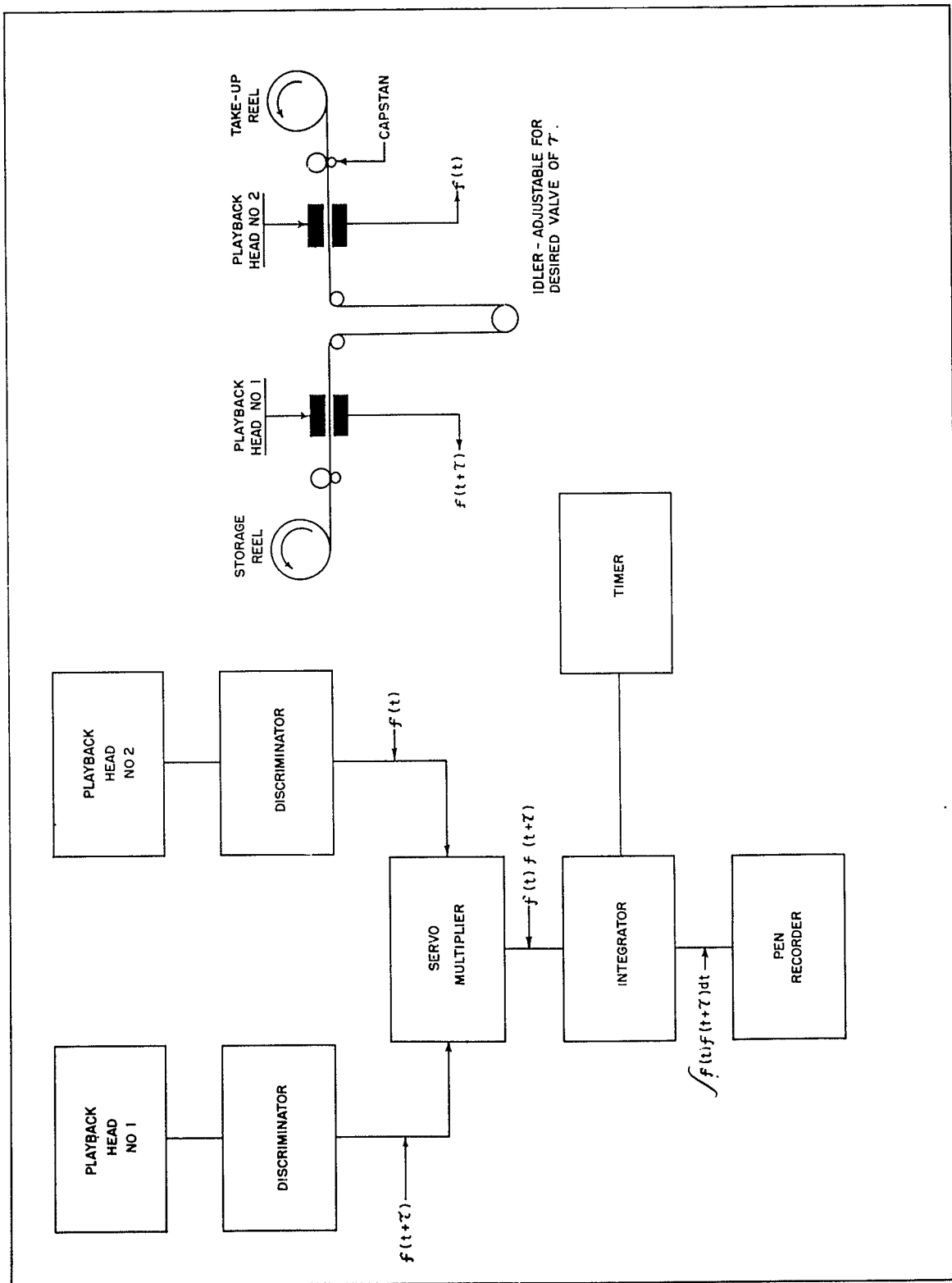


Figure 30. Electronic Autocorrelator

be considered stationary. Furthermore, the time spent in obtaining the autocorrelation, even by electronic means, becomes excessive if long samples are used. Theoretical investigations of the accuracy of the autocorrelation when described on a finite interval have been carried out by several investigators, and the subject will not be treated here.

In general it is not possible to obtain the autocorrelation function in closed form as the analytic expression for $f(t)$ is not known. By repeated evaluation of the integral for different values of the parameter τ a curve may be constructed for $\phi(\tau)$ however. Frequently it is then possible to construct artificially functions which closely fit the curve.

The autocorrelation is the basis of two closely related types of predictors. The first of these is frequently termed a discrete point predictor, as only discrete values of $\phi(\tau)$ are used. The predicted value, $f(t + \alpha)$ is expressed as

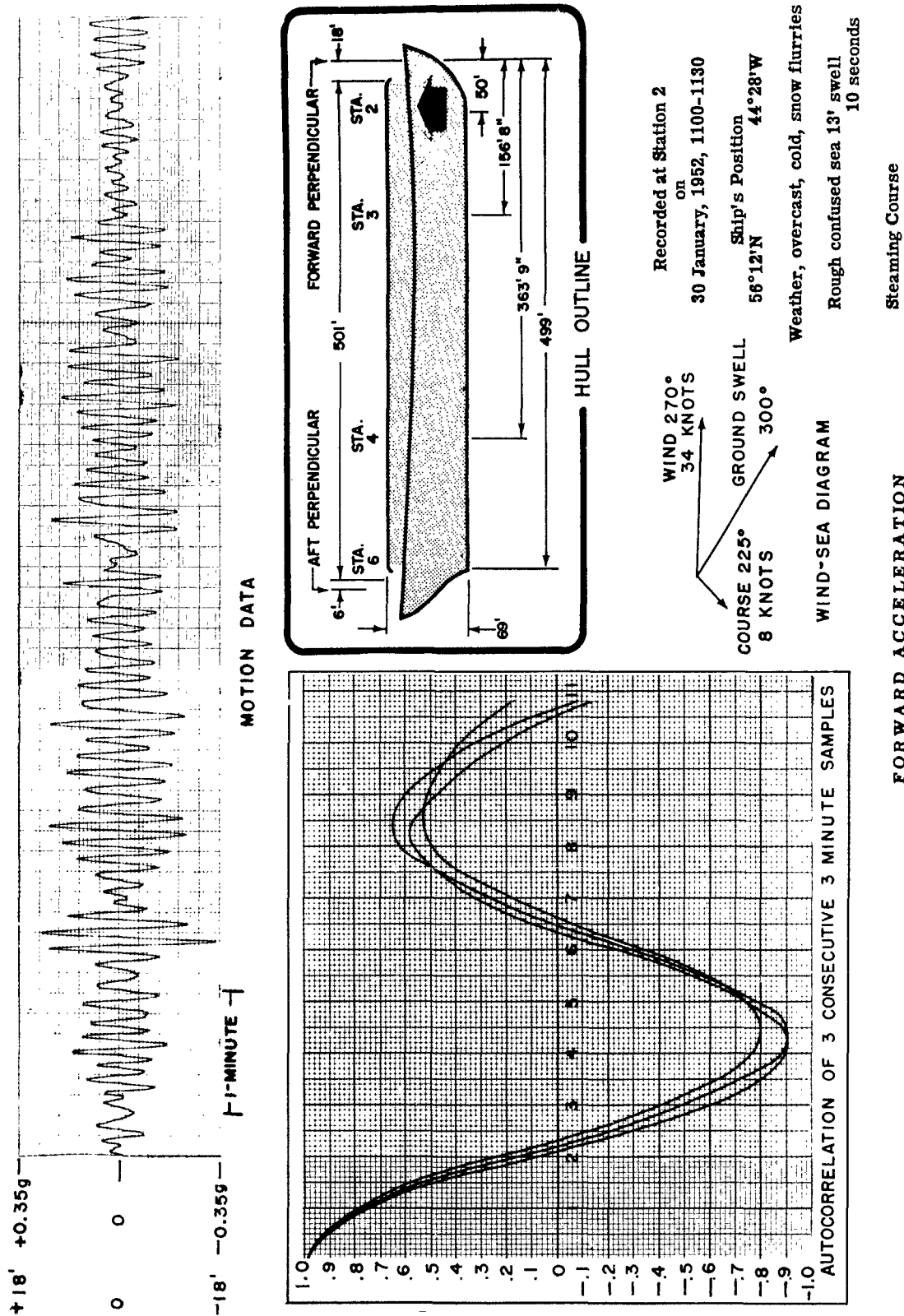
$$f(t + \alpha) = a_0 f(t) + a_1 f(t-1) + a_2 f(t-2) + \cdots + a_n f(t-n) = \sum_{i=0}^n a_i f(t-i)$$

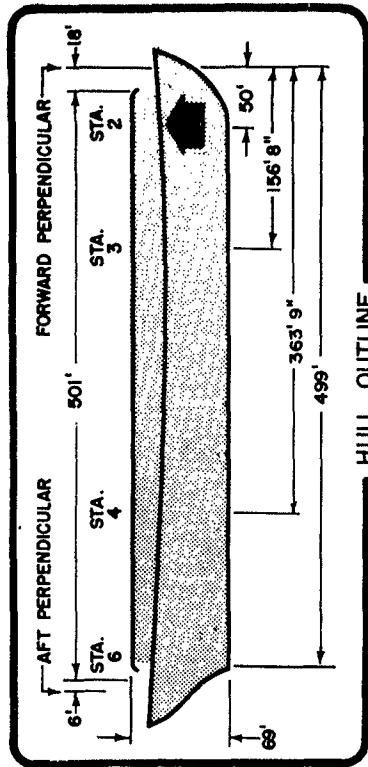
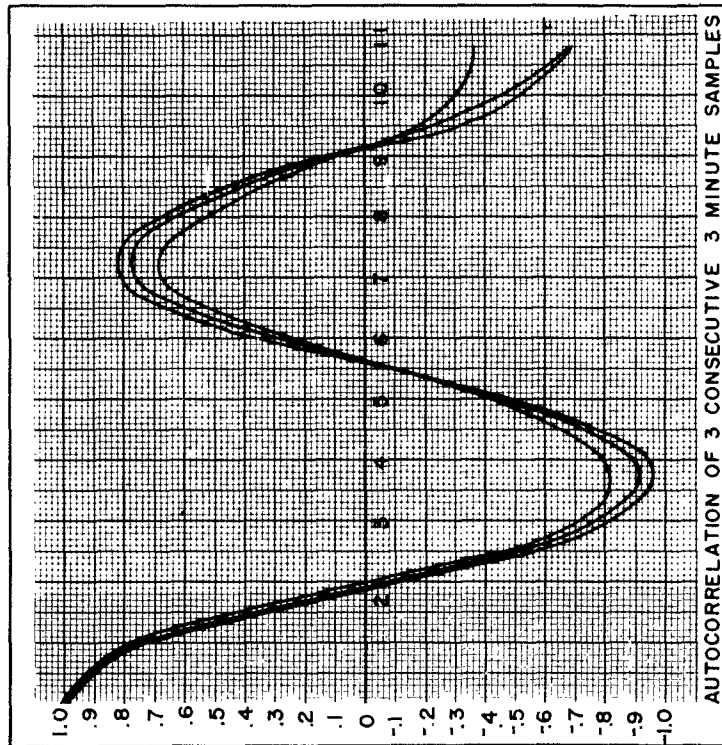
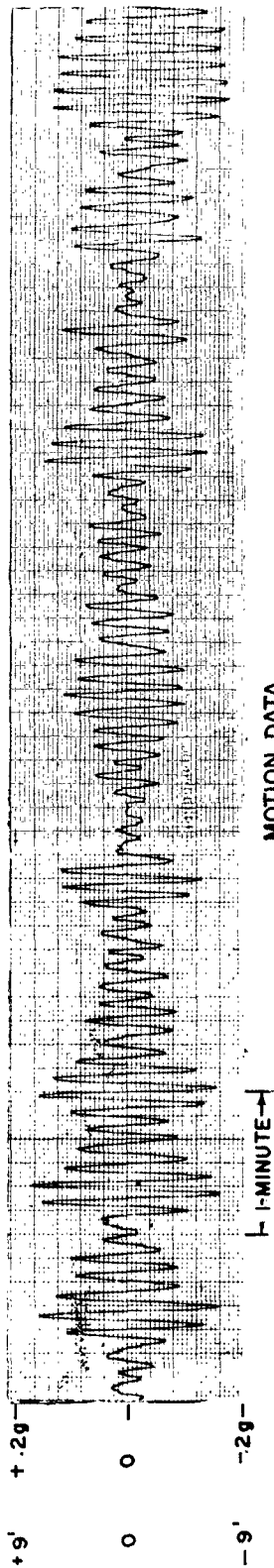
The a_i are weighting constants determined from the autocorrelation. Determination of the a_i requires the solution of n equations in n unknowns, which is a considerable drawback to the physical realization of a continuously operating predictor, especially if n is required to be large.

A natural extension of the discrete point predictor is the replacement of the summation by an integral, thus involving all values of the autocorrelation within the range: $0 < \tau \leq n$. Such a predictor is sometimes termed a Wiener-Lee predictor.

Autocorrelations have been obtained electronically with the equipment depicted in the block diagram — Figure 30. $f(t)$ is the motion record on the magnetic tape. The signal from one head is $f(t)$ and the signal from the other is $f(t + \tau)$. Different values of τ are obtained by changing the length of tape intervening between the two heads. The limiting value of $2T$ is the length of the data sample available. The product $f(t)f(t + \tau)$ is formed by a servo multiplier. Integration of the product is carried out by a feedback amplifier.

The autocorrelation in Figures 31 to 38 were obtained by this means, with the exception of the one noted, which was calculated on an IBM computer.





Recorded at Station 2
on
1 February, 1952 1510-1540
Ship's Position 47°25'N 46°28'W
Weather cloudy cold
7' ground swell 5 seconds period
Aircraft Recovery Operations in Progress

COURSE 330°
15 KNOTS

GROUND SWELL 300°

WIND 045°
21 KNOTS

WIND-SEA DIAGRAM

FORWARD ACCELERATION

U.S.S. Kula Gulf CVE-108

Figure 32. Sample of Autocorrelation

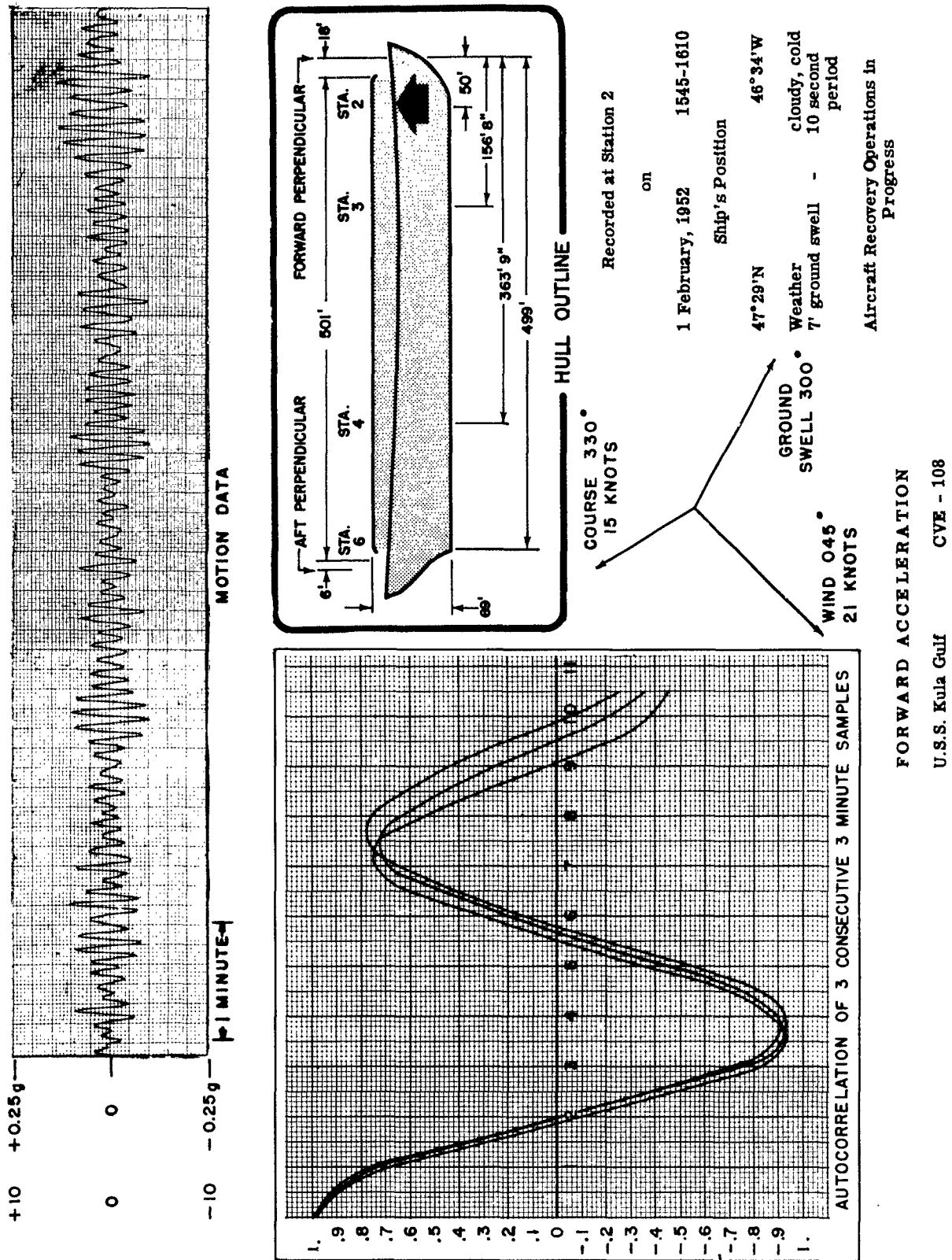
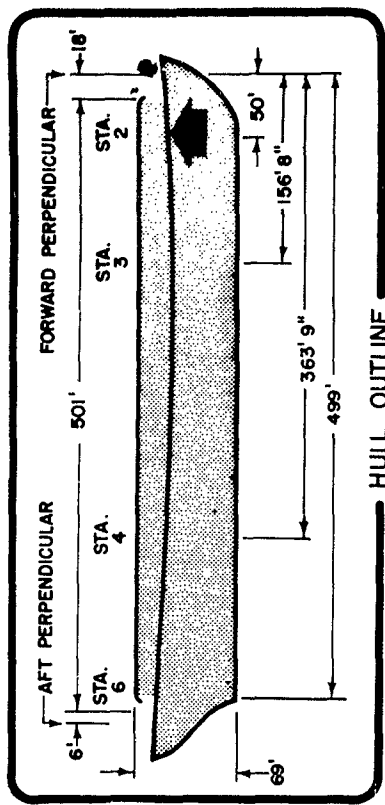
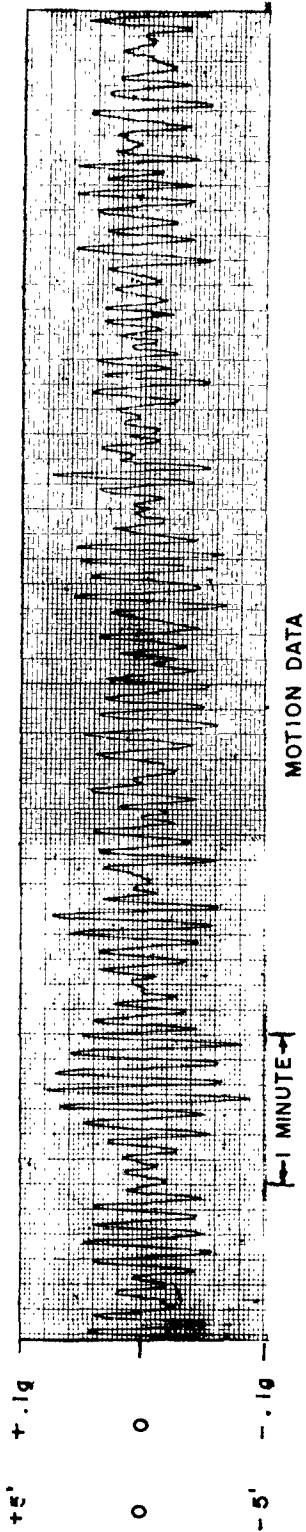


Figure 33. Sample of Autocorrelation



Recorded at Station 2
on
2 Feb. 1952 0950-1200

Ship's Position
49°19'N 46°23'W

Weather - cold, cloudy

6' Ground swell, 5 second period

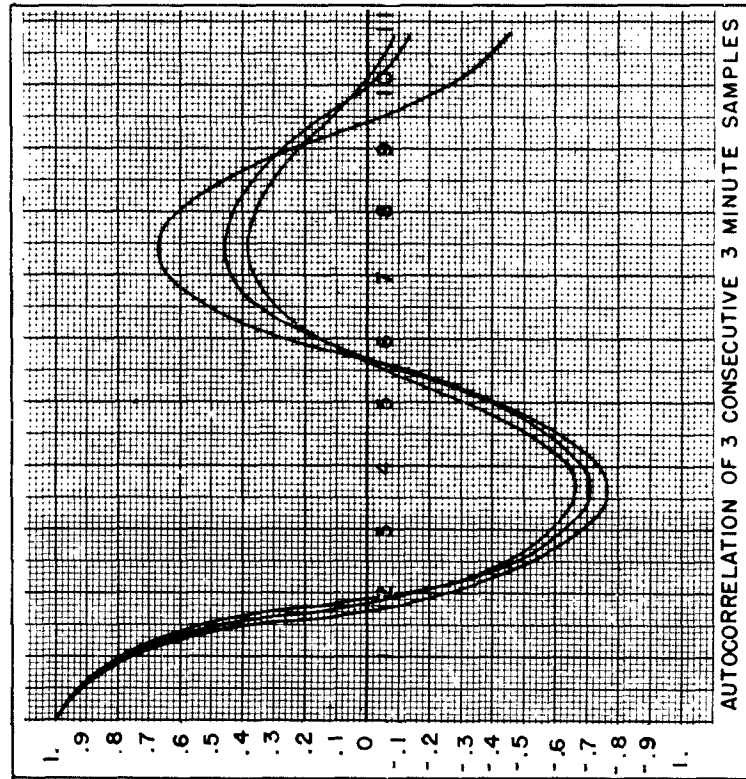
Aircraft Recovery Operations in Progress

WIND 202°
19 KNOTS

GROUND SWELL
240°

COURSE 250°
13 KNOTS

WIND-SEA DIAGRAM



FORWARD ACCELERATION
U.S.S. Kula Gulf CVE - 108

Figure 34. Sample of Autocorrelation

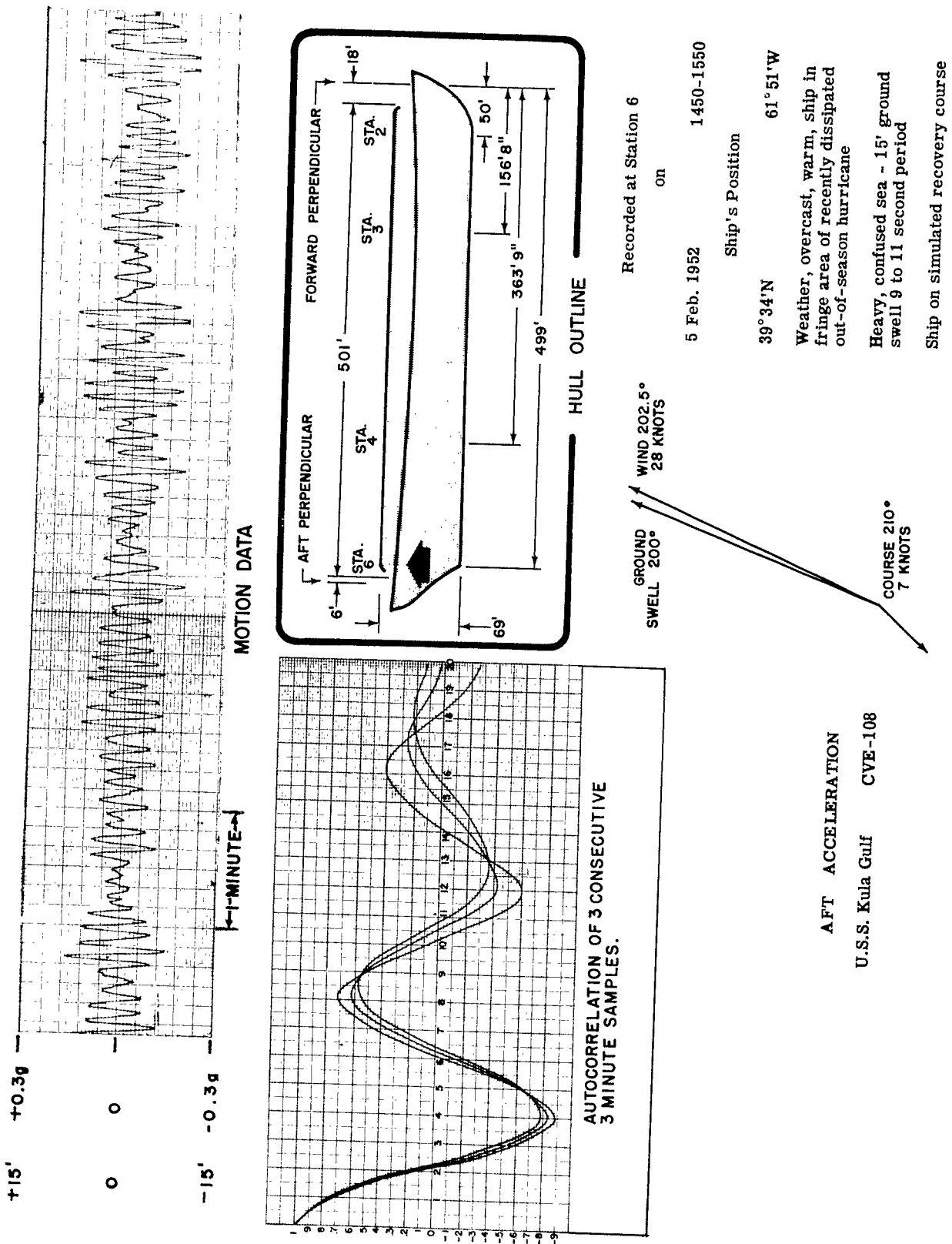


Figure 35. Sample of Autocorrelation

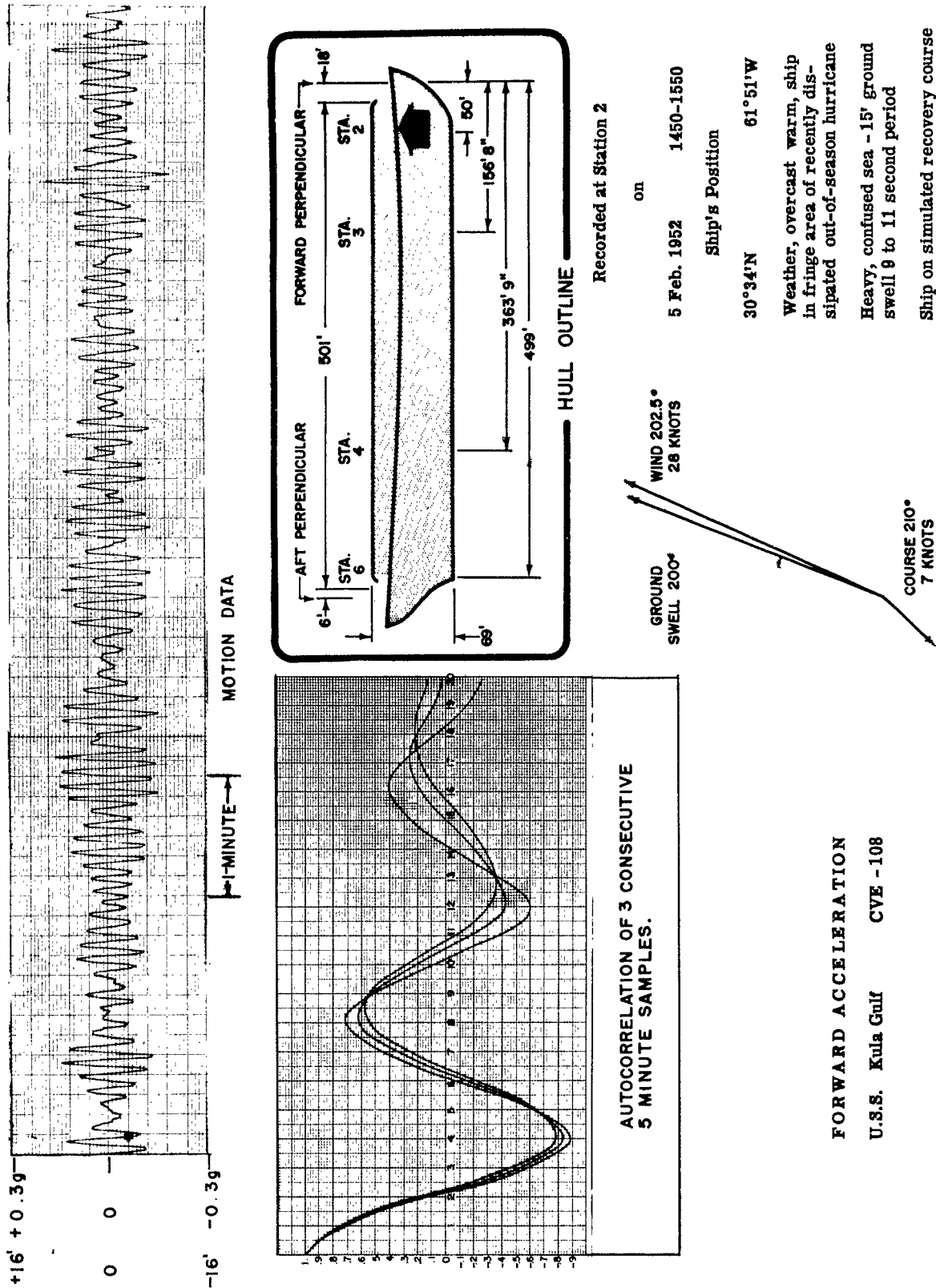
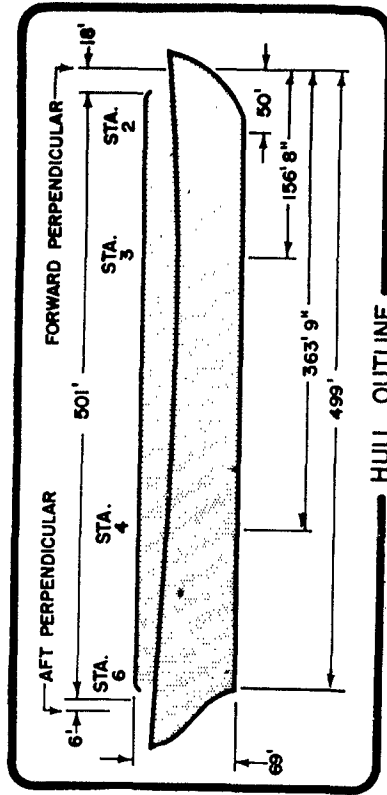
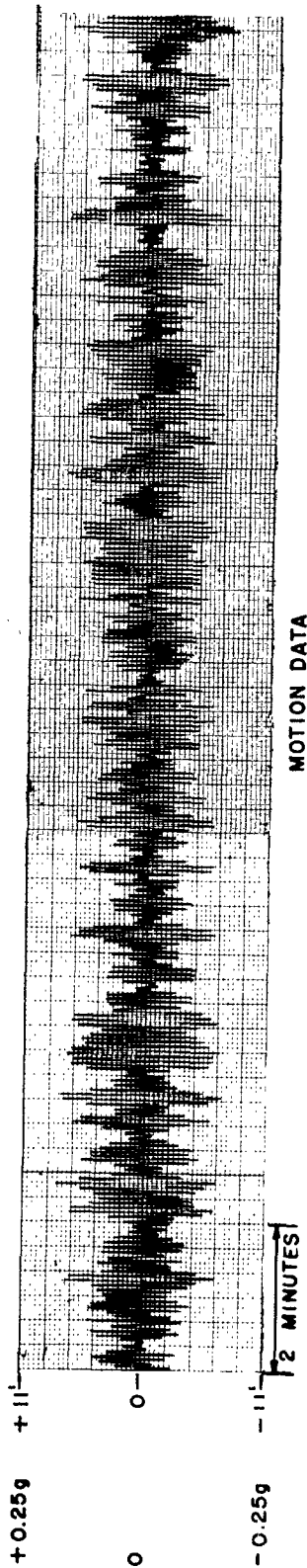


Figure 36. Sample of Autocorrelation



Recorded at Station 2 on 6 February, 1952 1410 - 1510

WIND 270°
10 KNOTS

GROUND SWELL
290°

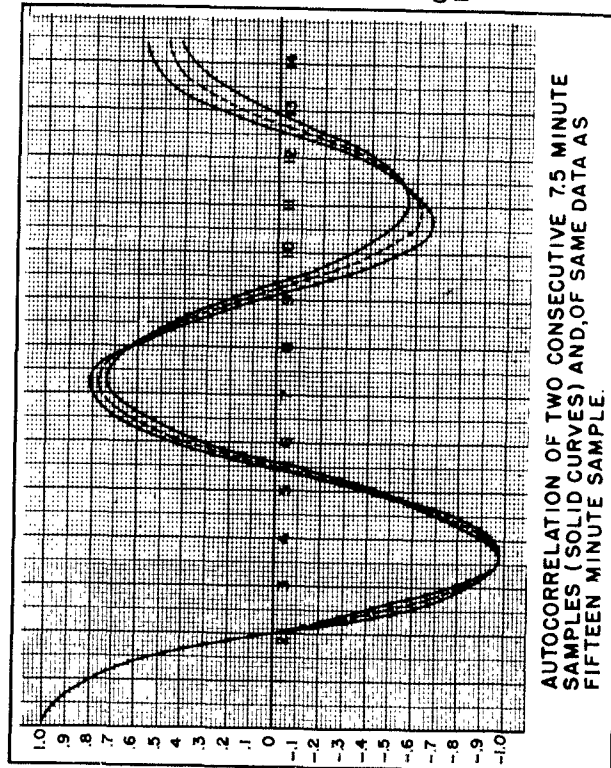
Ship's Position
28°24'N 67°28'W

Weather - cloudy, wind decreasing steadily

Sea moderately rough, 14' ground swell - 9 second period

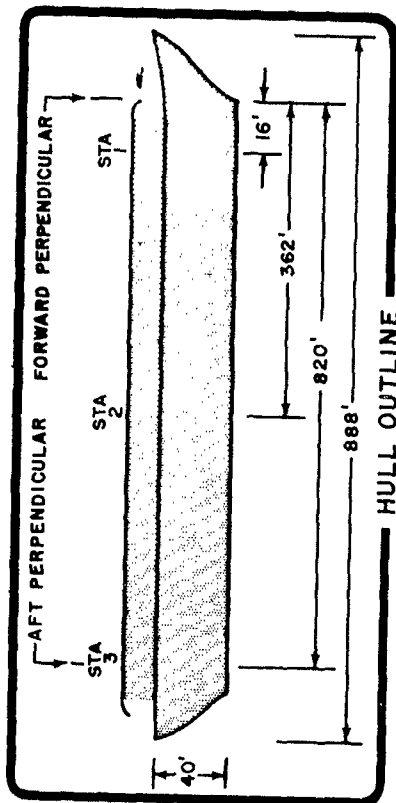
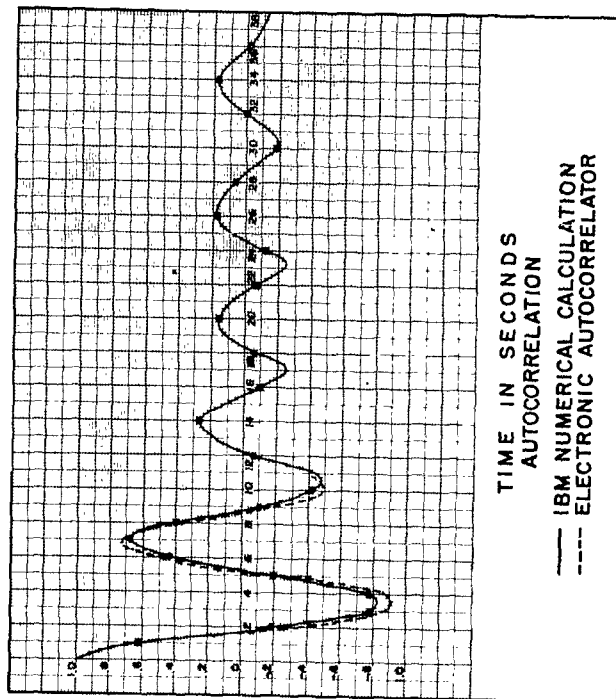
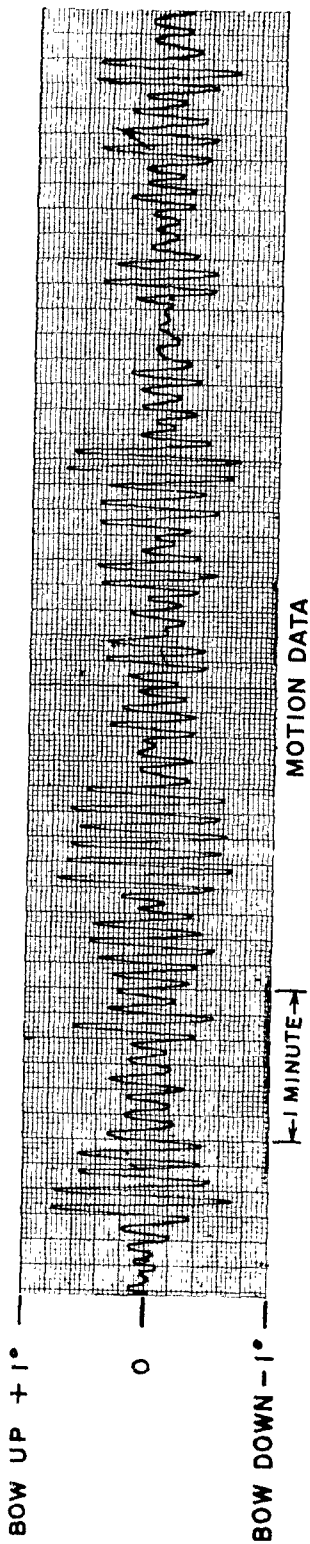
Steaming course - near recovery course

WIND SEA DIAGRAM



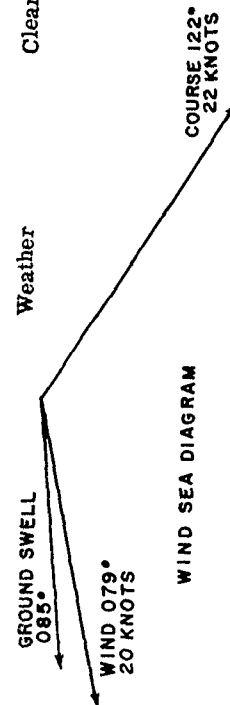
FORWARD ACCELERATION
U.S.S. Kula Gulf CVE - 108

Figure 37. Sample of Autocorrelation



Recorded on
6 June, 1952
Ship's Position
11° 39' N
57° 55.8' W
Weather
Clear

Moderate Sea
6' Ground Swell
3' Wind Waves



PITCH MOTION

U.S.S. Oriskany

CV-34

Figure 38. Sample of Autocorrelation

SECURITY INFORMATION—CONFIDENTIAL

One of the interesting features of these autocorrelations, although secondary to the purpose for which the autocorrelations were made, is the variation in the time of occurrence of the first positive maximum. The time of occurrence of this peak is determined by the period of the ship motion in pitch.

Figure 39a is a plot of the period of encounter, that is, the period between encounters of the ship with successive wave crests, versus the pitching period. The latter was determined from the autocorrelations. The former was computed from the aerological observations made at the time of recording and the two assumptions:

$$V = \frac{g}{2\pi T} \quad \text{where} \quad V = \text{wave velocity}$$

$$L = \frac{g}{2\pi T^2} \quad T = \text{wave period}$$

$$L = \frac{g}{2\pi T^2} \quad L = \text{wave length}$$

$$g = \text{gravitational acceleration}$$

Inspection of the curve shows that the points fall into two groups. If a straight line is drawn through the intersections for which the pitching period is equal to the period of encounter, it closely fits one of the groups (the points marked ●). The fit is closer, in fact, than the accuracy of the observed data justifies. The other group of points (marked 0) shows no relationship between the pitching period and the period of encounter.

These results are in excellent agreement with those obtained by British Admiralty workers in their experiments aboard the S.S. Ocean Vulcan. A similar curve was obtained and is reproduced in Figure 39b. Points comparable to the ones marked "0" on our curve were purposely omitted.

Attention is directed to two salient features of these curves. First it will be noticed that the pitching period of the ship is the same as the period of encounter whenever the period of encounter is greater than the natural period of the ship. Secondly, it is apparent that the points exhibiting considerable scatter, (the points marked "0") all occur for periods of encounter which are less than the natural period of the ship. Although complete understanding of these phenomena must be postponed, it is interesting to make certain deductions at this time and then later compare these theories with facts.

The first phenomenon would be explained if the response of the ship decreased very sharply above the natural frequency, and less

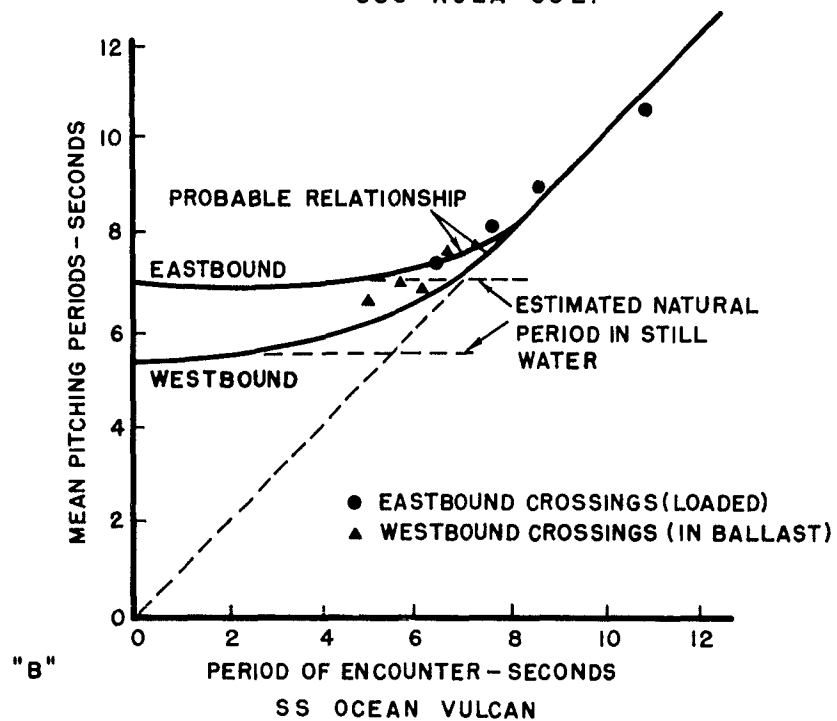
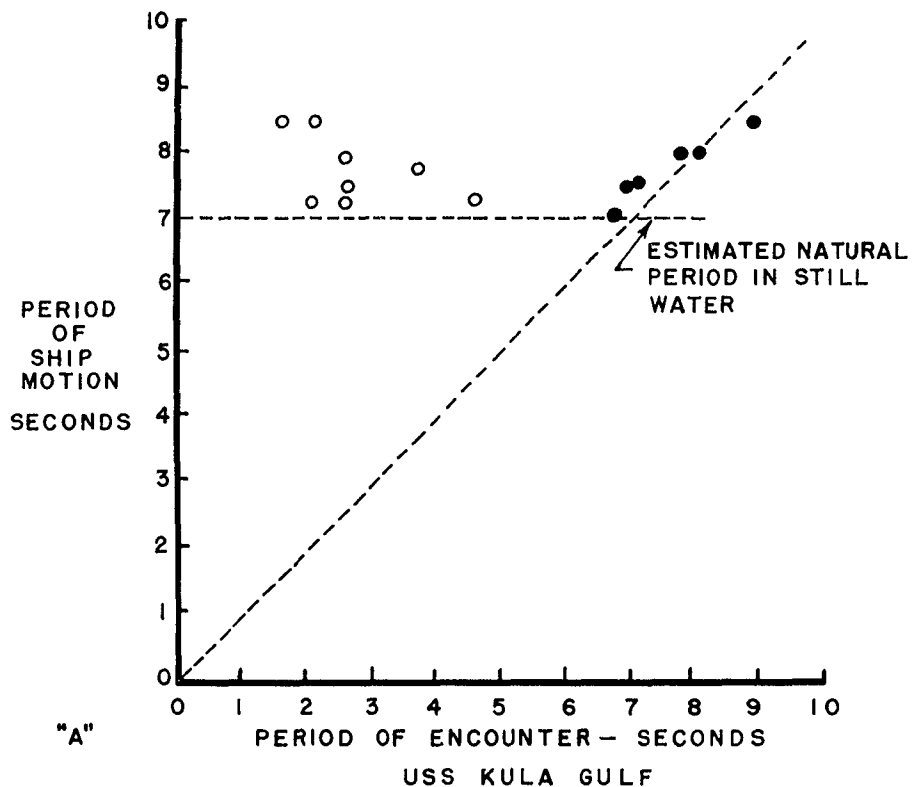


Figure 39. Relation of Pitching Period to Period of Encounter

sharply below the natural frequency. In other words, periods of encounter shorter than the natural period of the ship would evoke only extremely small response, whereas the response to periods of encounter longer than the natural frequency would be appreciable.

This theory explains away the second phenomenon very neatly when a knowledge of the manner of taking the data pertaining to the period of encounter is included. The observer simply recorded the data for the most prominent wave motion. If the period of encounter with the most prominent disturbance were shorter than the natural period of the ship, it would be expected that the ship would respond to some other disturbance which might be smaller in amplitude (and hence less obvious to a human observer) but of a lower frequency, and therefore a more favorable one for the sake of exciting ship motion.

Further support to this theory is given by the fact that at no time was the period of the motion found to be shorter than the natural period of the ship.

Despite the effort which was expended in obtaining these autocorrelations, they were not used in establishing the predictability of ship motion. There were several reasons for this. An attempt to construct an artificial function which would fit the autocorrelation over the required interval met with surprising results. Several functions were found, all offering a reasonably close fit, but widely different in nature and representing prediction criteria of very different predictors. Furthermore, the necessary accuracy could not readily be achieved in extracting the autocorrelation from motion records. Attention was directed, therefore, to another method of analysis which, it was hoped, would not present these difficulties.

Autocorrelation functions are probably a much less familiar form of analysis than the one which is considered next: amplitude spectra. Actually the two are closely related and there is no information contained in one that is not contained in the other. The mathematical theory relating the two is not simple, however, and will not be presented here. It is sufficient to say, without mathematical rigor, that the square of the absolute value of the amplitude spectrum and the autocorrelation function constitute a Fourier-transform pair. The square of the amplitude spectrum is termed the power-density spectrum.

As the frequencies present in ship motion are, for the most part, less than one cycle per second, the amplitude spectrum is not easy to obtain in practice. A typical process for obtaining the spectrum is illustrated in Figure 40. Frequency transformation is accomplished by successive recording and playback at the frequencies and tape speeds shown until the frequencies are 420 times their original values. Because

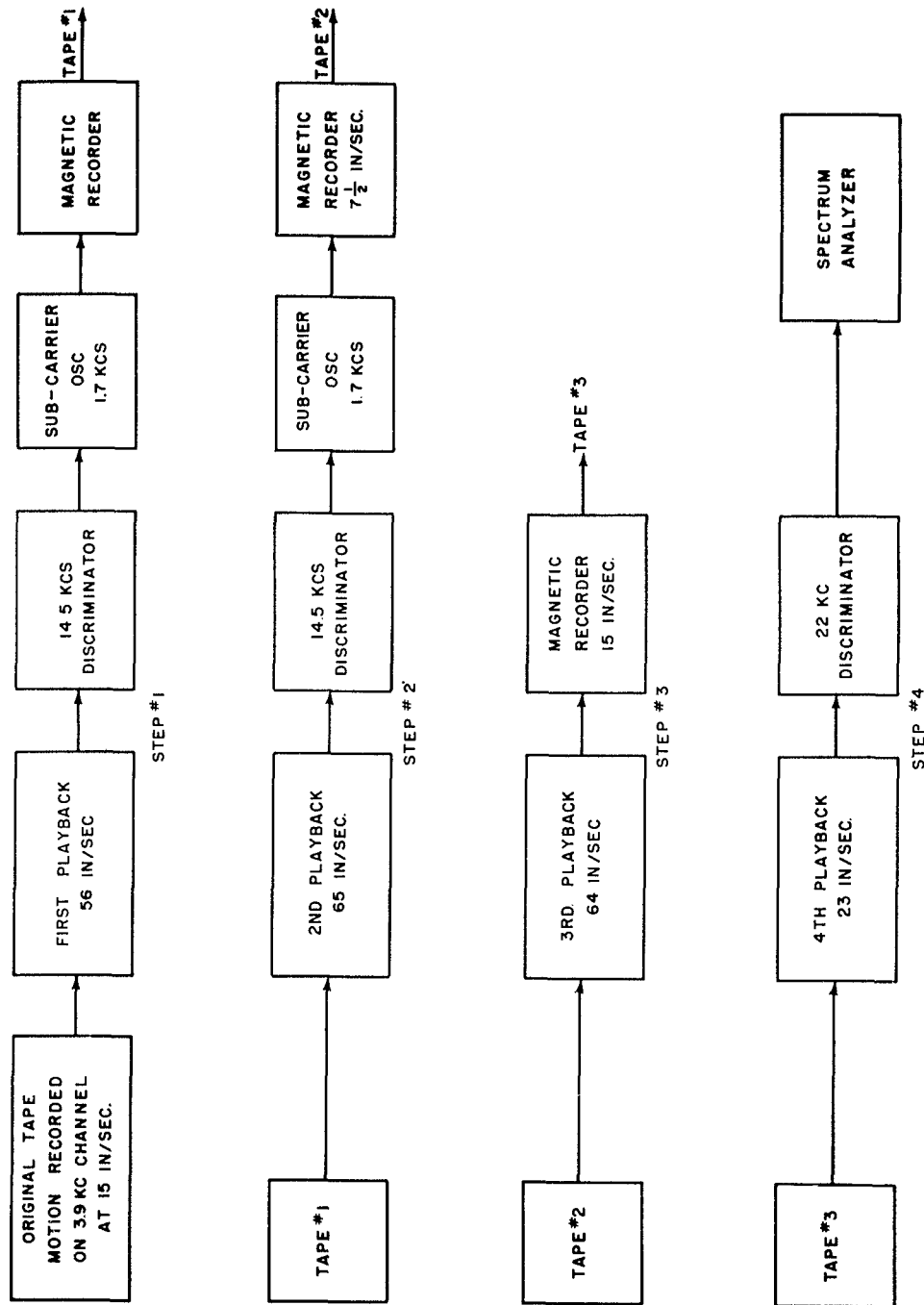


Figure 40. Electronic Spectrum Analysis - Method I

of the transformation to higher frequencies, the information contained in a standard 2400-foot tape is compressed into a tape about five-and-one-half feet long. This tape is spliced into an endless loop for final playback. A conventional wave-analyzer may then be used to investigate the spectrum, the damping of the meter needle being adequate to integrate the energy in each component frequency over the abbreviated length of the tape.

Several examples of amplitude spectra are presented in Figures 41 to 44. The motions from which these spectra were obtained are shown in Figure 45. The variations in the frequencies of maximum amplitude are attributable to variations of the period of encounter, just as the time variations of the first positive maxima of the autocorrelation were.

Theoretical investigations which were being conducted collaterally indicated at about this time that the behavior of the spectra above the frequency of maximum amplitude was of crucial importance in the determination of ship-motion predictability. The reason for this is that the high-frequency portion of the spectrum largely determines the characteristics of the derivatives, and the derivatives in turn are vital to any method of prediction. This is best illustrated by considering a Taylor Series predictor — a type sometimes employed in a modified form in fire-control work. Although this is not a type of predictor under consideration for the current problem, it is ideal for the present purpose as it expresses the predicted value as a function of the derivatives, and it is a mathematical form familiar to most engineers.

If the value of some function $f(t)$ and its derivatives is known at $t = t_0$, the value at some other time, $t = t_0 + a$ may be found from the expansion in Taylor series.

$$f(t_0 + a) = f(t_0) + af'(t_0) + \frac{a^2 f''(t_0)}{2!} + \frac{a^3 f'''(t_0)}{3!} + \cdots + \frac{a^n f^{(n)}(t_0)}{n!} + R$$

It is obvious upon inspection of this series that the predicted value depends only on the instantaneous value of the function, the derivatives of the function, and certain constants. It is therefore the nature of these derivatives which is of primary importance.

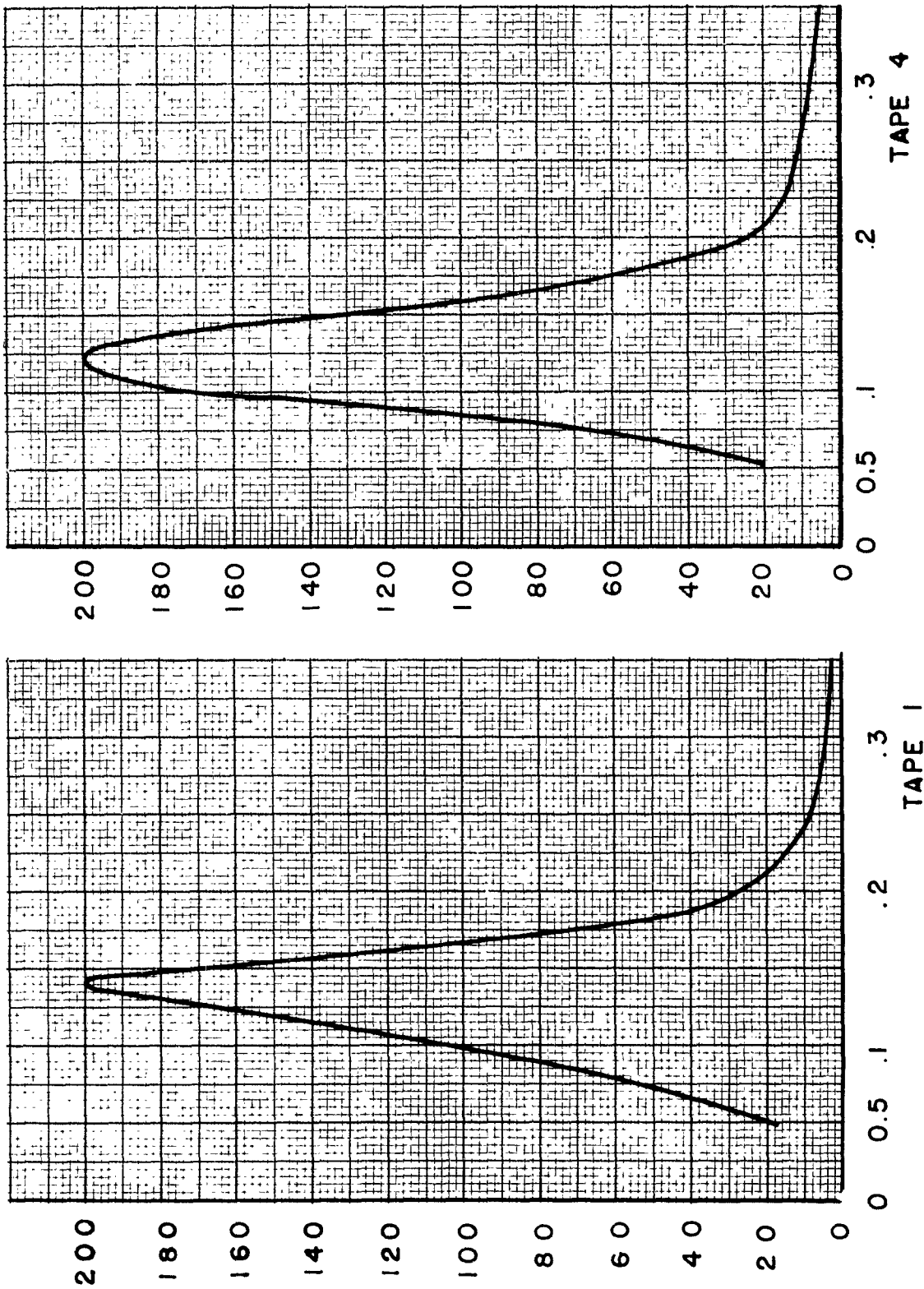


Figure 41. Samples of Amplitude Spectra

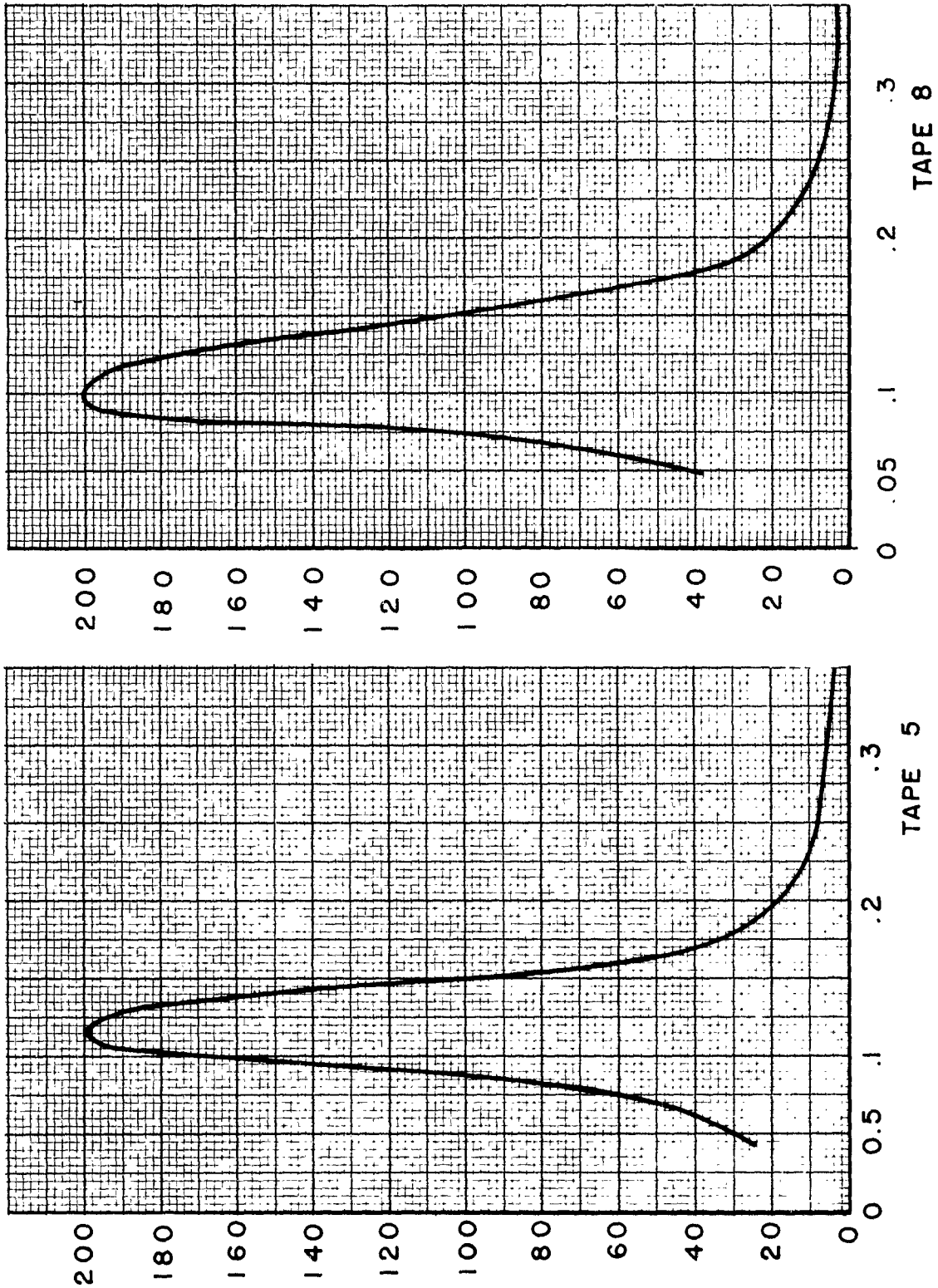


Figure 42. Samples of Amplitude Spectra

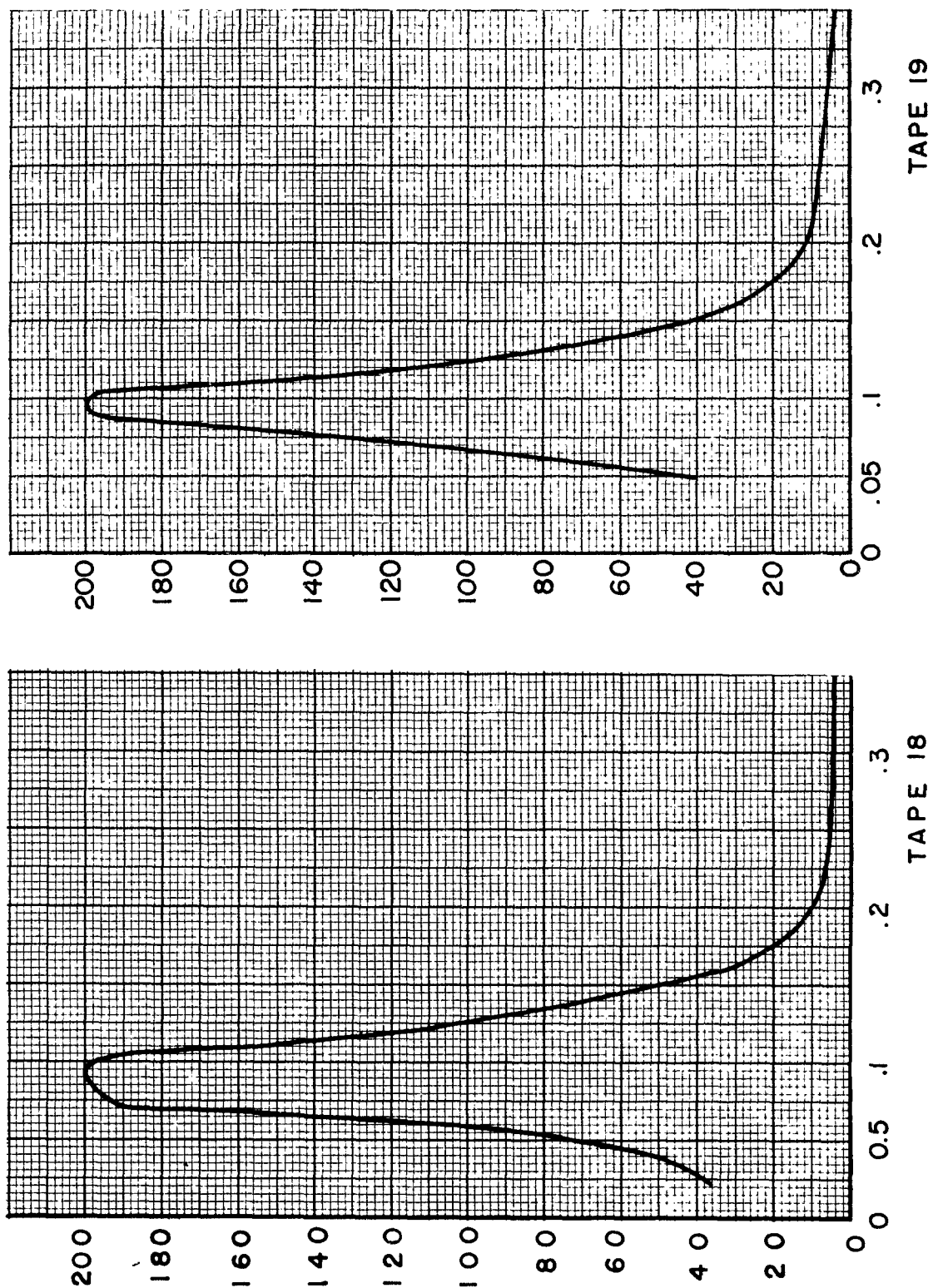


Figure 43. Samples of Amplitude Spectra

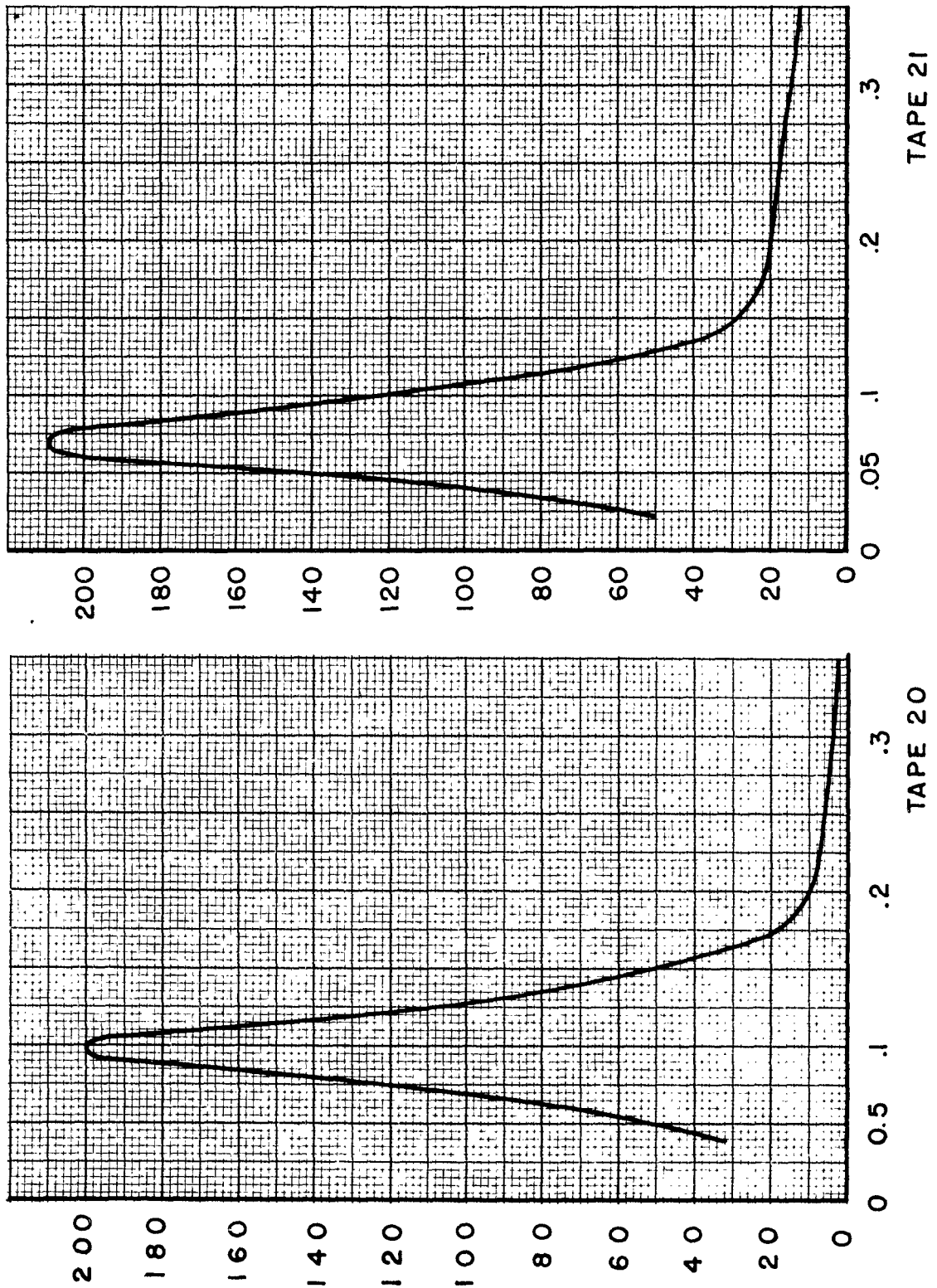
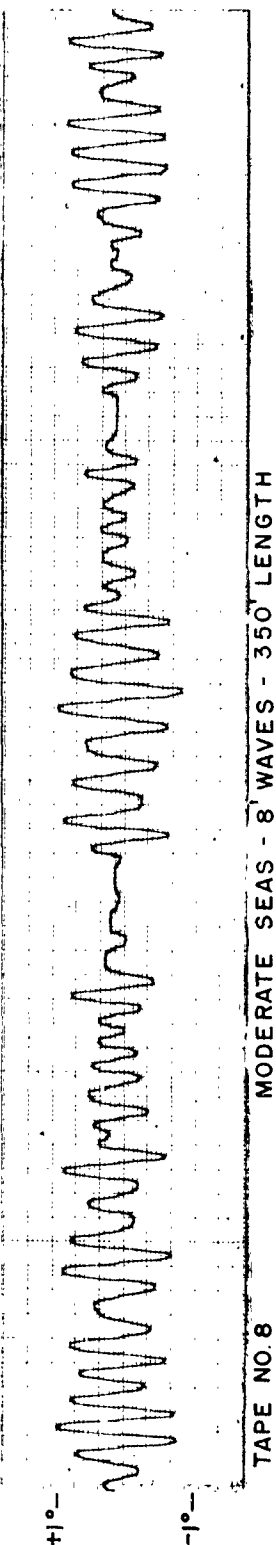
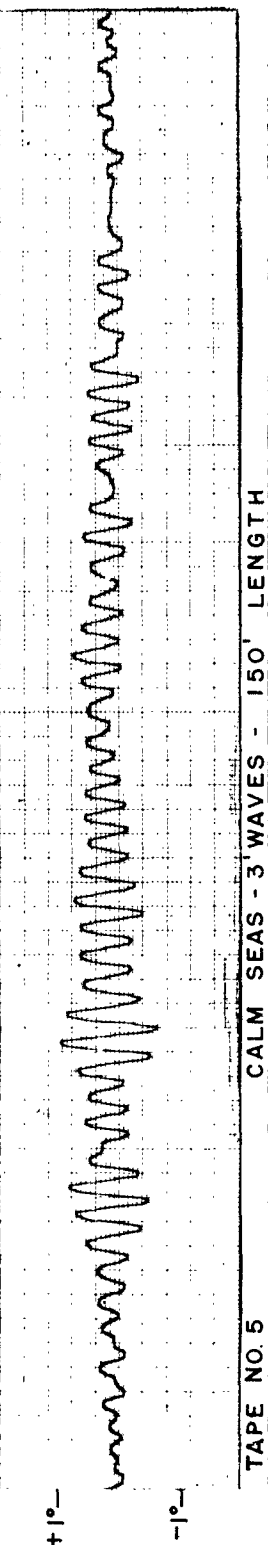
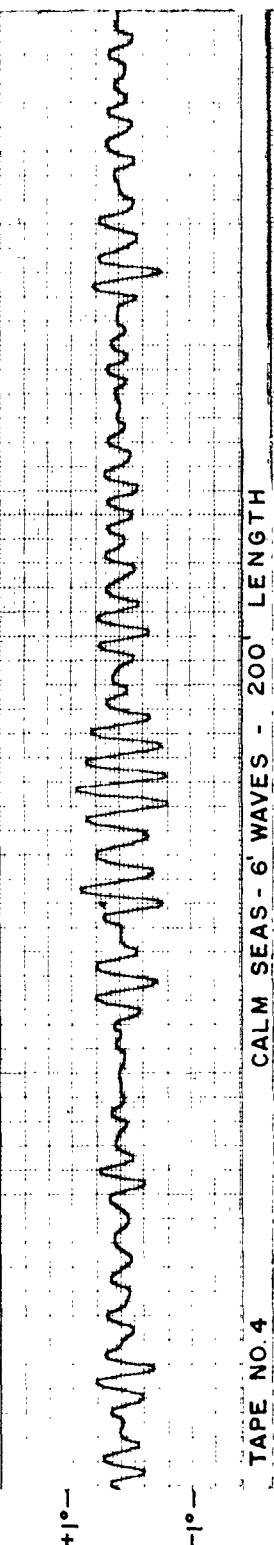
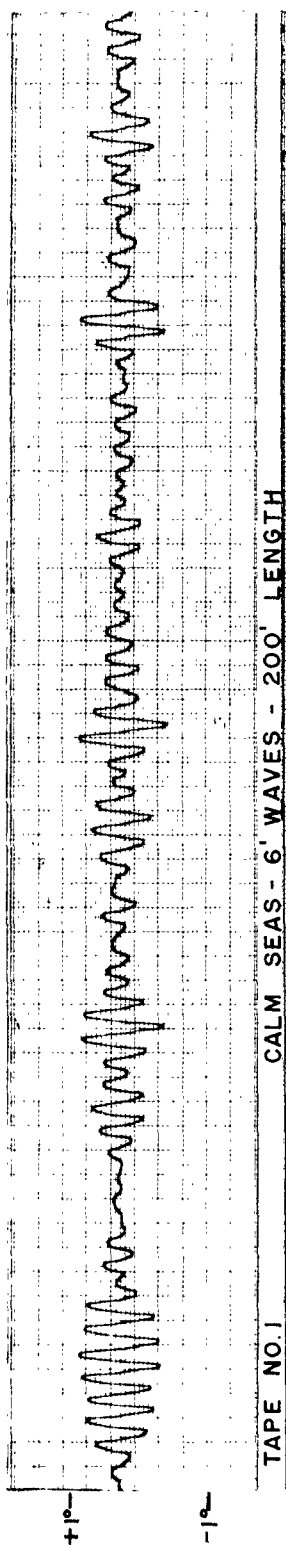


Figure 44. Samples of Amplitude Spectra



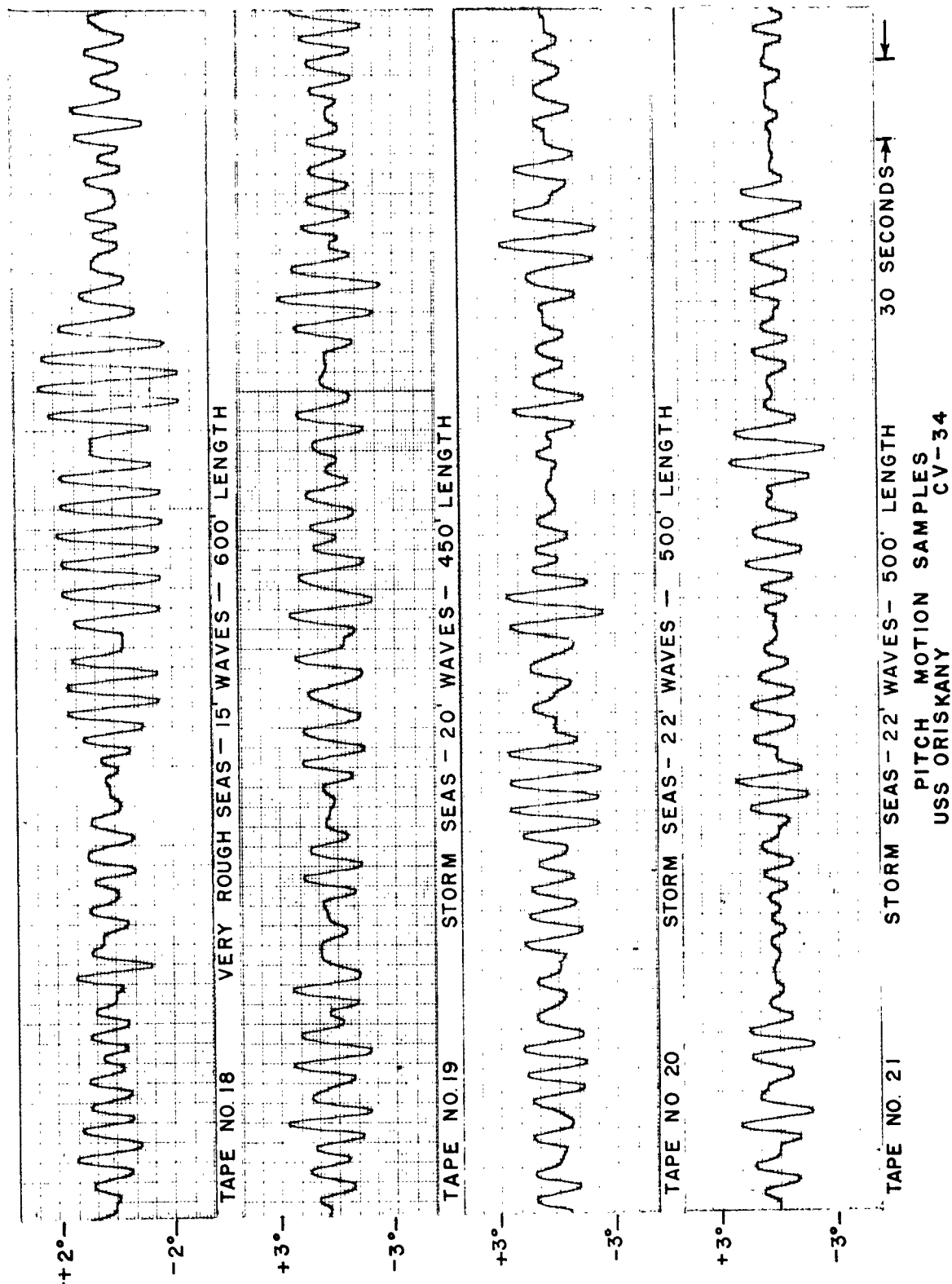


Figure 45. Pitch Motion Samples

Differentiation of a function representable by an amplitude, or power density spectrum, amplifies the higher frequencies by 6 db per octave. This may be illustrated by considering two functions of equal amplitude whose frequencies differ by an octave, $A \sin \omega t$ and $A \sin 2 \omega t$. The first derivatives have amplitudes $A \omega$ and $2A \omega$ respectively and the amplitude of one is double that of the other. The ratio of the amplitudes of the second derivatives is 4, and with each successive differentiation, the ratio is again doubled. In the same way, the differentiation process amplifies all the higher frequencies of a continuous spectrum by an amount depending on the frequency; namely, 6 db per octave or 20 db per decade.

A graphic illustration of the behavior of the derivatives is shown in Figure 46. The pitch spectrum and the spectra of the first three derivatives of pitch obtained from one of the U.S.S. Oriskany recordings are shown. The derivatives were obtained by arbitrarily choosing the amplitude at 0.1 cps as zero level and then plotting the new curves by increasing the amplitudes of the pitch spectrum by 6, 12, and 18 db per octave above the reference frequency. The amplitudes of frequencies lower than the reference frequency were decreased by like amounts. The arbitrary choice of zero-level controls the size, but not the shape, of the spectra of the derivatives. The dashed line, included for reference, has a slope of 6 db per octave.

Above 0.2 cps the pitch spectrum decreases by about 6 db per octave. This decrease almost exactly counteracts the increase introduced by one differentiation, so that in this region the spectrum of the first derivative is nearly flat. The spectra of the second and third derivatives accordingly increase by 6 and 12 db per octave respectively.

Considering the manner in which the amplitudes of the derivatives in Figure 46 increase with frequency, it would be expected that the derivatives themselves would show evidence of a large high-frequency content — i.e., noise. Inspection of Figure 47 shows that this is exactly the case. The figure shows the pitch motion from one of the records made on the U.S.S. Oriskany together with pitch velocity, pitch acceleration, and the derivative of pitch acceleration, all obtained by differentiation of pitch. The amplitudes of the derivatives have been adjusted to show them in true relation except for the derivative of pitch acceleration, which is reduced by a factor of four.

Fortunately, it is possible to obtain pitch acceleration without using differentiation. If the forward and aft accelerometers are roll-stabilized only, the difference of their outputs is identically equal to pitch acceleration. The pitch acceleration record of Figure 48 was obtained by this method. Comparison of this record of pitch acceleration with that of Figure 47 shows one very prominent difference.

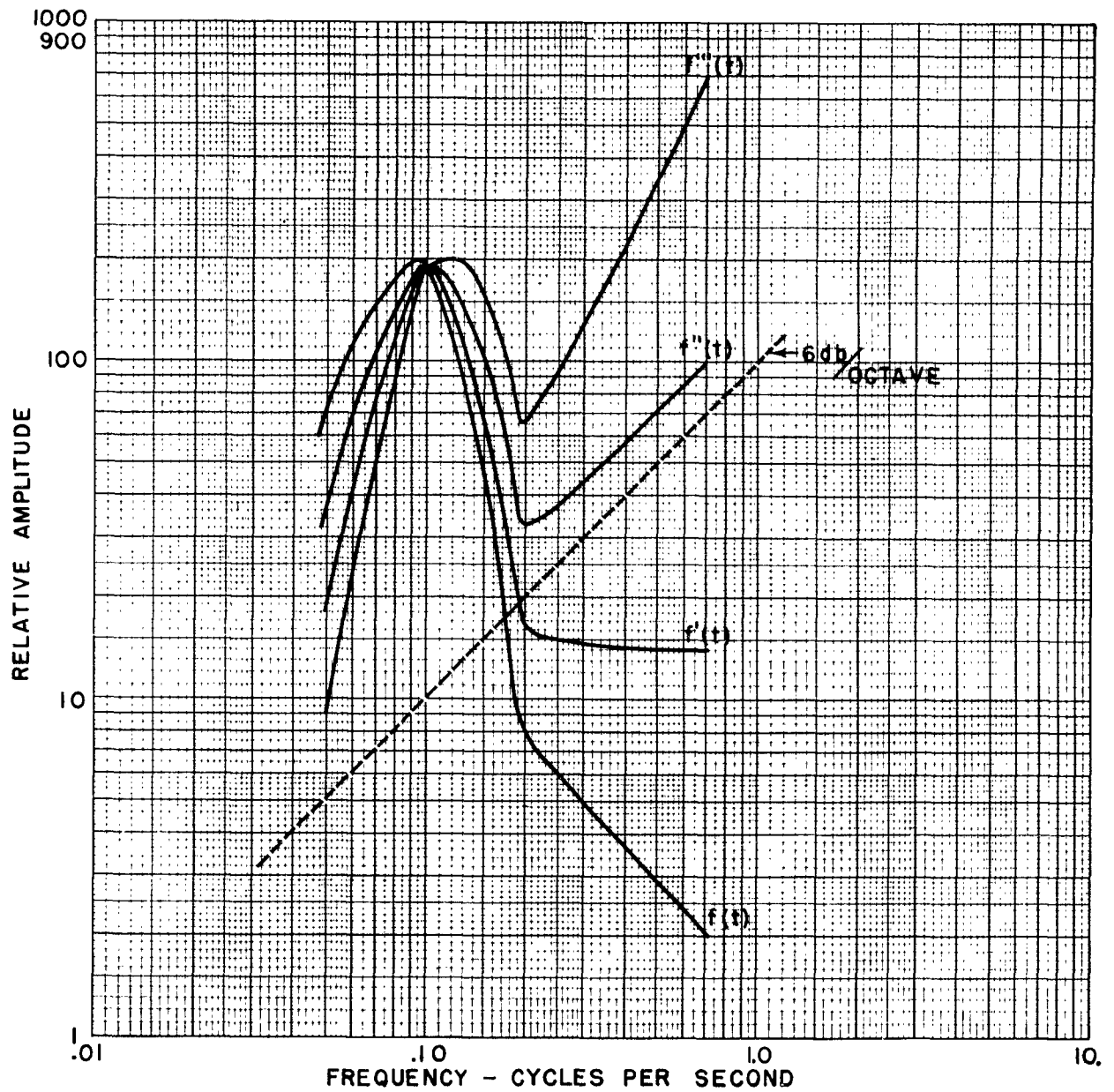


Figure 46. Amplitude Spectrum of Pitch - First Three Derivatives Determined Graphically

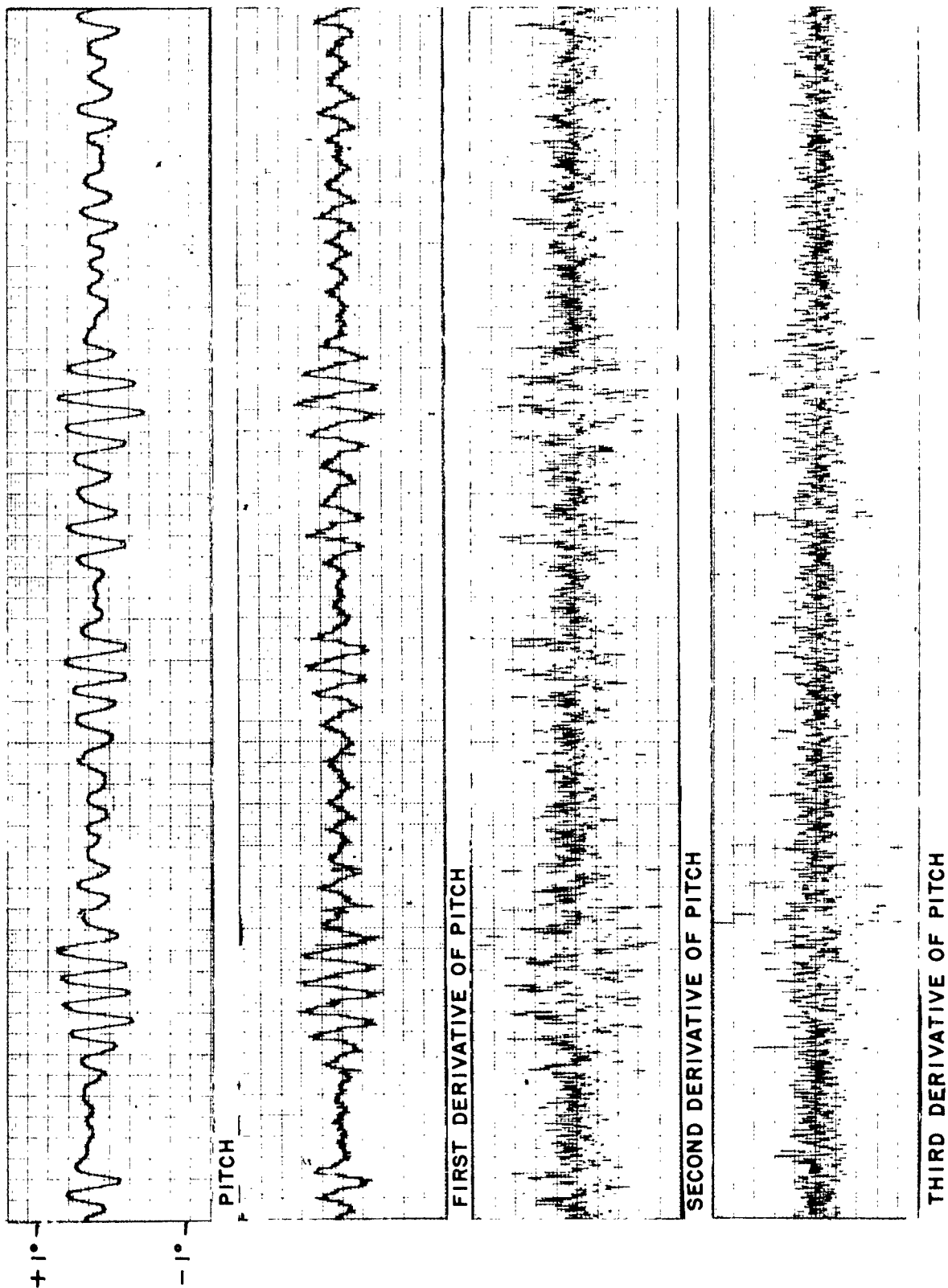


Figure 47. Pitch Motion of USS Oriskany and First Three Derivatives
Obtained by Differentiation

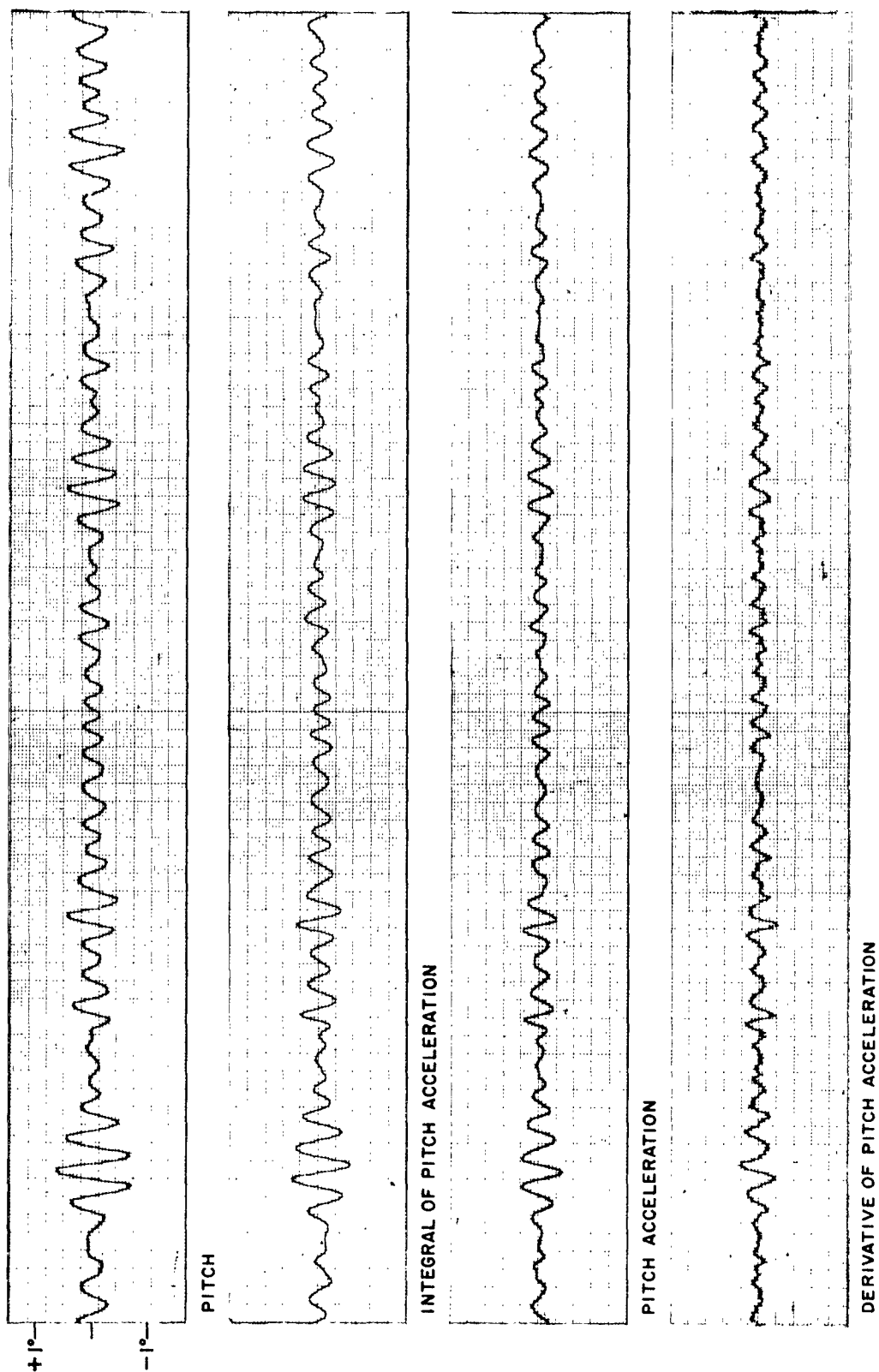


Figure 48. Pitch Motion of USS Oriskany and First Three Derivatives
Obtained from Pitch Acceleration

Pitch acceleration obtained directly is remarkably free from noise, whereas pitch acceleration obtained by differentiation is decidedly not. The only conclusion is that the process of measuring, recording, and playing back the data has introduced noise foreign to the true spectrum of the motion. When this composite function of noise and ship motion is twice differentiated, the noise completely dominates.

In view of the noise contamination noted in the pitch signal, it becomes evident that more refined methods are necessary if true spectra of the motion are to be obtained. Although the logical starting place would be with the shipboard installation, considerable minimization of the effects of noise in obtaining spectra from existing records is possible.

One simple and effective method of reducing the effects of noise is to measure the spectrum of pitch acceleration rather than pitch. The pitch spectrum is then obtained by subtracting twelve db per octave from the spectrum of pitch acceleration. The advantage of this method arises from the fact that pitch acceleration is obtained by a subtraction process. Any noise due to wow and flutter of the tape recorder will be subtracted out, as will any other noise which is present equally in both signals.

Another increase in the accuracy of the spectrum may be achieved by taking into account the shortcomings of certain instruments and processes, and by obtaining the spectrum by a judicious combination of the spectra from two or more instruments. The portion of the spectrum from each instrument which is utilized, is chosen on the basis of the response of the instrument. Thus, although a pitch spectrum obtained from pitch acceleration is superior on the basis of high frequency noise, as indicated above, accelerometers are susceptible to drift. Hence the low-frequency portion of the spectrum is probably more accurate if obtained directly from the pitch record.

In addition to the afore-mentioned procedures which should be observed if accurate spectra are to be obtained, a third and perhaps much more obvious one is that every effort must be made to keep the noise, introduced during the analysis process, down to an absolute minimum.

In view of this last consideration, it was believed that the spectra obtained previously might be incorrect because of noise introduced during the multiple recording and playback processes. A different method of obtaining the spectra, which did not require repeated playback and rerecording of the original data, was therefore employed.

The method involved the use of electronic filtering by means of a Reeves Analogue Computer. The basic filter section diagram is depicted in Figure 49.

It may be shown that this filter section has a bandwidth R_1 , a center frequency $R_2 m_1 m_2 m_3$, and a gain at the center frequency of $1/R_1$. This system is particularly convenient to use, as the bandwidth and frequency controls are independent. Each point on the spectrum is determined by integrating the rectified output of the filter over the entire length of the data and recording the terminal value of the integral. Sufficient amplifiers are available to obtain three points on the spectrum at a time.

Figure 50 is a composite pitch spectrum obtained by combining the pitch spectra determined directly with that resulting from graphical integration of the pitch acceleration spectrum. The dashed portion of the composite was obtained directly from the pitch spectrum which is shown in Figure 51. The solid portion was obtained by graphical, double-integration of the pitch acceleration spectrum of Figure 52.

Comparison of the pitch spectrum of Figure 51 and the pitch acceleration spectrum of Figure 52 shows that the two curves have roughly the same configuration over the high-frequency portion. Previously, it was pointed out that the high-frequency portion of the uncorrected pitch spectrum depended almost entirely on noise introduced during the measuring and recording process. The next and somewhat disquieting question which immediately presents itself is whether the pitch acceleration spectrum is truly representative of the ship motion or whether it is also dependent on noise contamination.

Further evidence of the possibility of noise contamination is contained in Figure 48, which is a record of pitch and pitch acceleration typical of the records from which the composite pitch spectrum was obtained. The first integral and first derivative of pitch acceleration have been included. Examination of the derivative of pitch acceleration shows that there is a very noticeable high-frequency content, although it is somewhat smaller than the high-frequency content of the derivative of pitch obtained by differentiation, presented in Figure 47. It has been shown, however, that the derivative of pitch obtained by differentiation of the pitch signal differs widely from the true pitch velocity because of the noise corruption of the pitch signal, emphasized by the differentiating process. This question of whether the pitch acceleration is contaminated by noise is an extremely important one in the prediction problem because of the effect of spurious noise content on the derivatives, as was discussed previously.

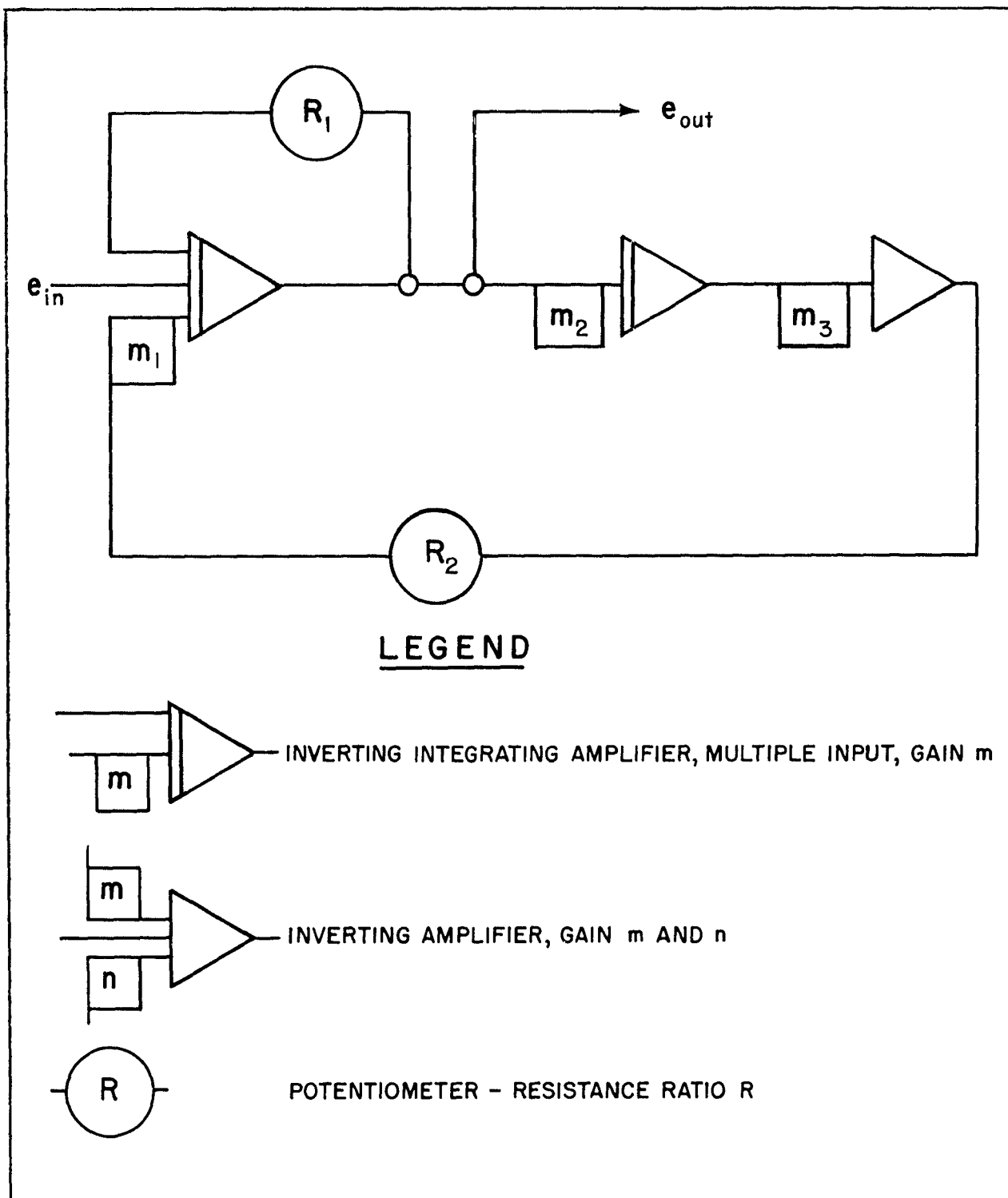


Figure 49. Filter Section Used in Electronic Spectrum Analysis - Method II

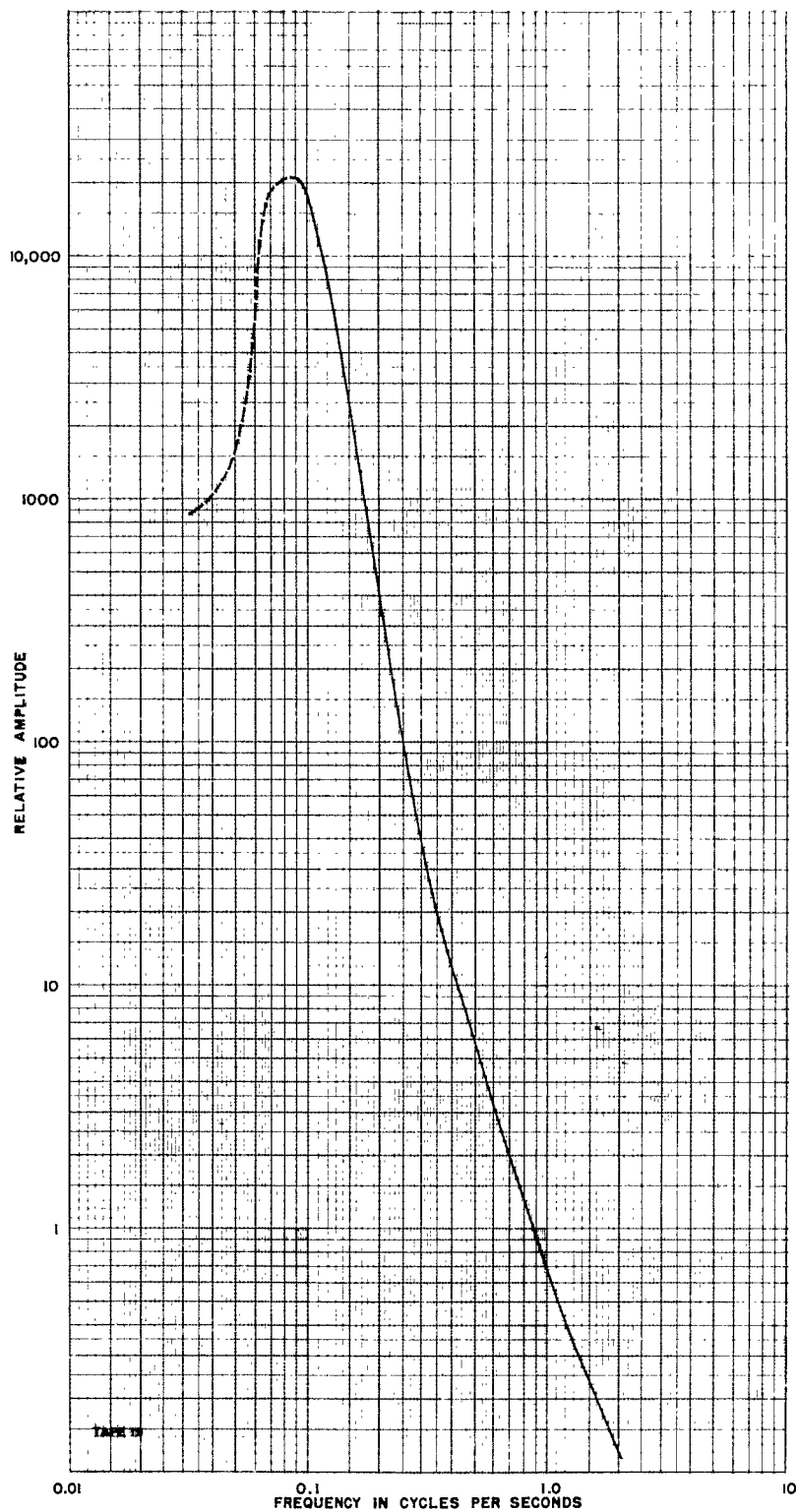


Figure 50. Composite Pitch Spectrum

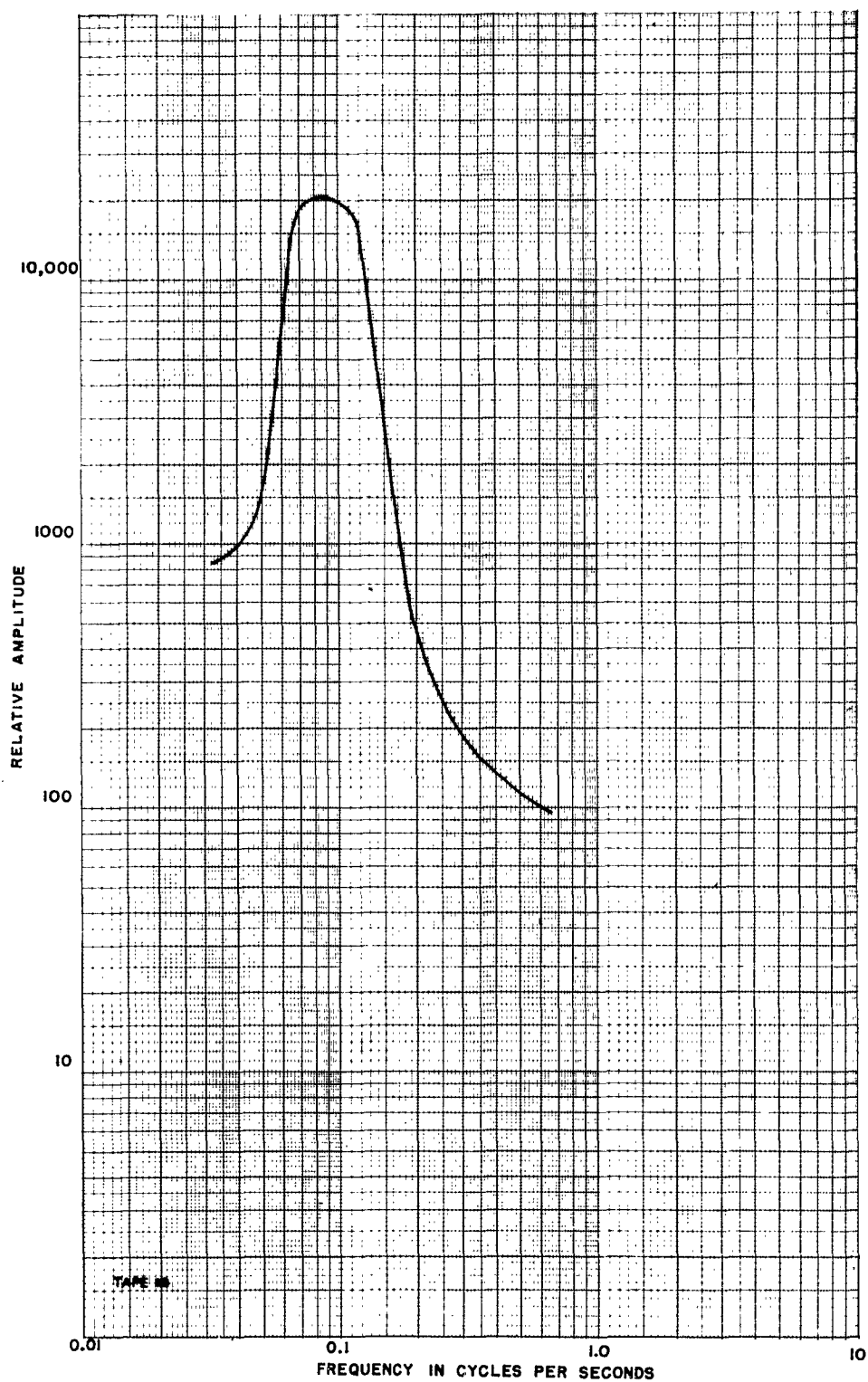


Figure 51. Pitch Spectrum Determined from Stable Element

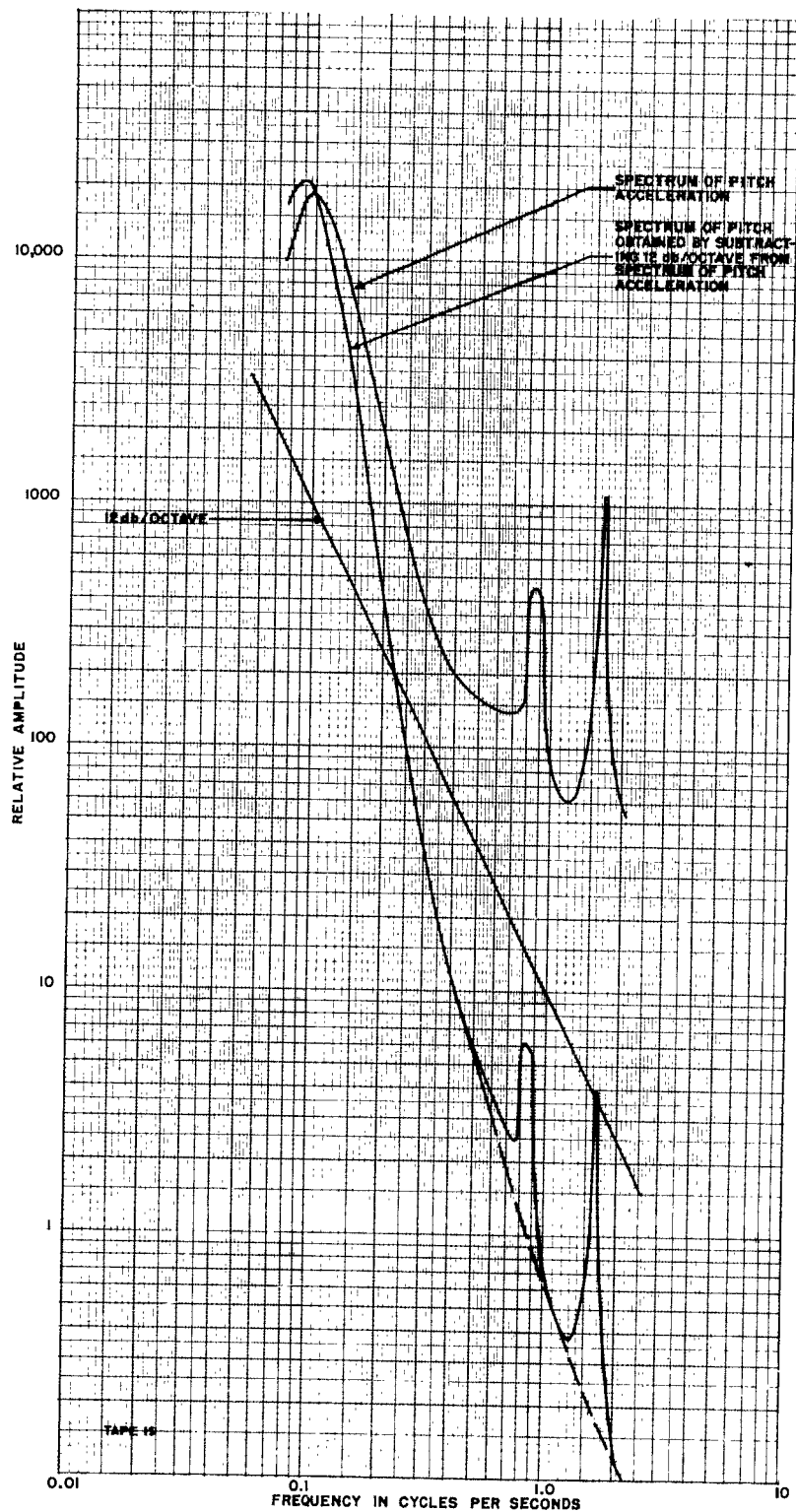


Figure 52. Pitch Spectrum Determined from Pitch Acceleration

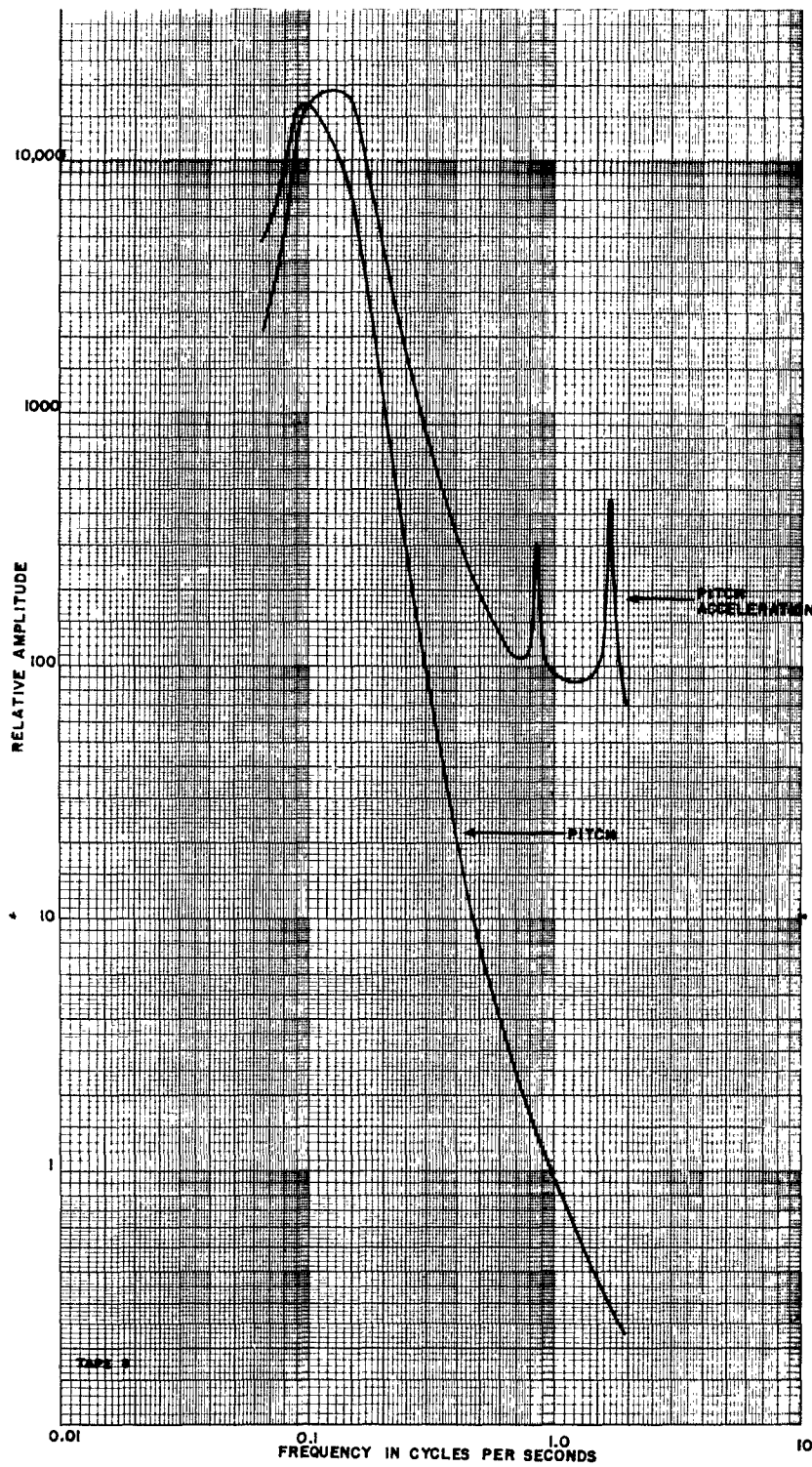


Figure 53. Pitch Spectrum Determined from Pitch Acceleration

SECURITY INFORMATION—CONFIDENTIAL

For the sake of the prediction problem, it became imperative to determine the spectrum of the ship as accurately as possible and hence the number of derivatives that could be employed in making the prediction.

Two courses leading to the determination of the true spectrum were open and the decision between the two was basically an economic one. One course was to undertake another shipboard instrumentation program, incorporating the most noise-free measuring and recording instruments and techniques that could be obtained or devised. The second alternative involved theoretical work which would give some indication of what high-frequency content should be expected in ship motion records.

In accordance with the decision to follow the second of the two alternatives a twofold program was commenced. The first part of this program dealt with a consideration of the motion of a ship model in response to the excitation of waves of differing characteristics in a model basin, and in addition a study of the frequency distribution of the exciting function that was liable to be encountered at sea. This work is recounted in the following Section.

In the second part of the program, the vibrations of the ship and the manner in which they contributed to the ship motion recordings were studied.

This work covered "ship noises" from sources such as slamming and vibrations due to the propulsion machinery, in the frequency range extending up to 10 cps, and is described in Section IX.

section VIII data analysis II

At the conclusion of the preceding section a twofold program of further study was outlined. It is significant that one part of this dual program is identical with one of the two methods of study considered at the very beginning of the project, but not the one selected; namely, a study of the transfer function of the ship and the nature of the surface disturbance considered as an input, or forcing function.

The immediate and important objective of this part of the program was to determine whether the spectra which had been obtained from ship-motion records were reasonable. In particular, it was important to know whether the spectra obtained from ships dropped off as rapidly as the true spectra, or whether noise, foreign to the actual spectra, made the decrease on the high frequency side of the peak appear more gradual than it really was. If the latter were the case, it would have a radical effect on the prediction problem, as it would mean that by more noise-free instrumentation one or more terms might be included in the prediction equation, and therefore effort should be expended on improving instrumentation and data-handling techniques.

The technique employed to determine the accuracy of the spectra of ship motion is one commonly used by electronics engineers, but will be reviewed briefly here. Basically it consists in a determination of the transfer function of the ship by two methods, and a subsequent comparison of the results.

Figure 54 shows two methods of determining the transfer function. The first method (a) consists of applying an input to the ship of constant amplitude and variable frequency. The output — as degrees of pitch when plotted as a function of the input frequency — describes the transfer function.

In the second method (b) a completely random input is applied to the ship. The spectrum of the output, in this case, is the transfer function.

In both these methods there is one assumption which must be made. It is necessary to assume that the ship responds linearly to amplitude variations of the input. Whether or not this assumption is justifiable, it was decided to proceed on this basis for want of an alternative.

The application of these techniques to the problem at hand depends on the fact that the transfer function is invariant regardless of how it is determined. The first method is suitable for determining the transfer function of a model in a model basin, where close control of wave height and frequency is available. The frequency spectra presented in the preceding section may be considered as transfer functions determined by the second method if one rather unjustifiable assumption is made. The one necessary assumption is that the surface disturbance of the ocean is completely random. All evidence points to the fact that the surface disturbance is not completely random, but by keeping the shortcomings of this assumption in mind at least useful results may be inferred.

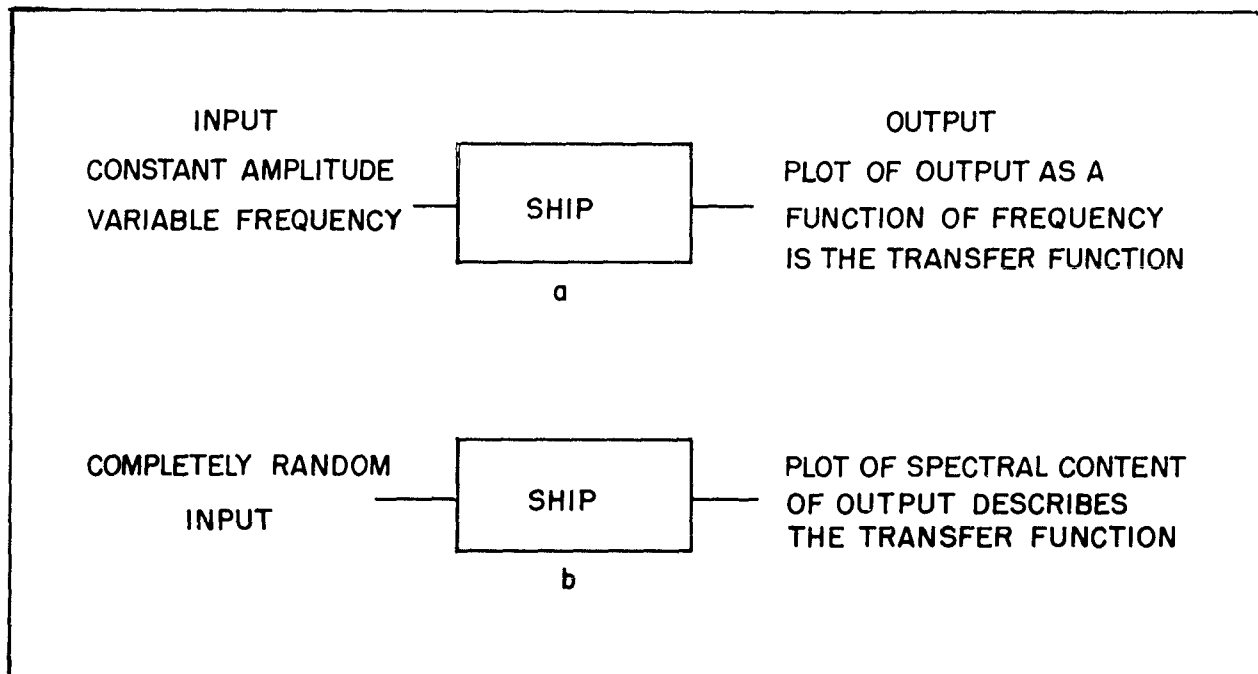


Figure 54. Methods of Determining Transfer Function

Comparison of the model basin transfer function with the transfer function determined from actual ship-motion records, could yield one of three results, depending on whether the transfer function of the ship decreased with increasing frequency above the main peak, (1) faster, (2) the same or (3) slower than that of the model.

If the assumption that the surface disturbance was completely random were justifiable, and if there were no noise contamination in the transfer function obtained from ship-motion records due to the recording and playback process, it would be expected that the two transfer functions would be almost the same. There would be small differences because of vibrations of the ship not present in the model, and other factors, it is true, but substantially the functions would be nearly equal.

The effect of noise due to the recording and playback process would be to make the decrease of the transfer function of the ship more gradual than the decrease of the model transfer function. On the other hand, if the sea were not completely random (which is the actual case), the effect would be to make the ship transfer function decrease more rapidly than that of the model.

The primary results of the model basin study are shown in Figure 55. Here the transfer function of the ship as determined by the model studies, is superimposed on a spectrum of the ship. The interpretation is not difficult. Since it is known that the surface disturbance is not completely random it must be inferred that the reason the transfer function of the ship does not drop off more sharply than the transfer function of the model is that there is noise contamination in the ship spectrum. The close agreement of the two curves indicates to us, however, that the spectra which had been obtained were reasonable; the error being at worst one or two orders of magnitude, and not four or five as was feared.

Admittedly there are many loopholes in this technique. Since the final result was qualitative rather than quantitative, and since the cost of the work was negligible compared to the cost of further work aboard ship with more refined equipment and techniques, it was considered an expedient choice.

The actual experiments of the first model studies were carried out at the David Taylor Model Basin by Model Basin personnel assisted by several Bell Aircraft Corporation engineers. The objectives of the first tests were to determine the natural period of a ship, and to determine the response to waves of known physical dimensions. Although it would have been desirable to use a model of the U.S.S. Oriskany (CV-34) for these tests, none was available, and a model of the U.S.S. Coral Sea (CVB-43) was substituted.

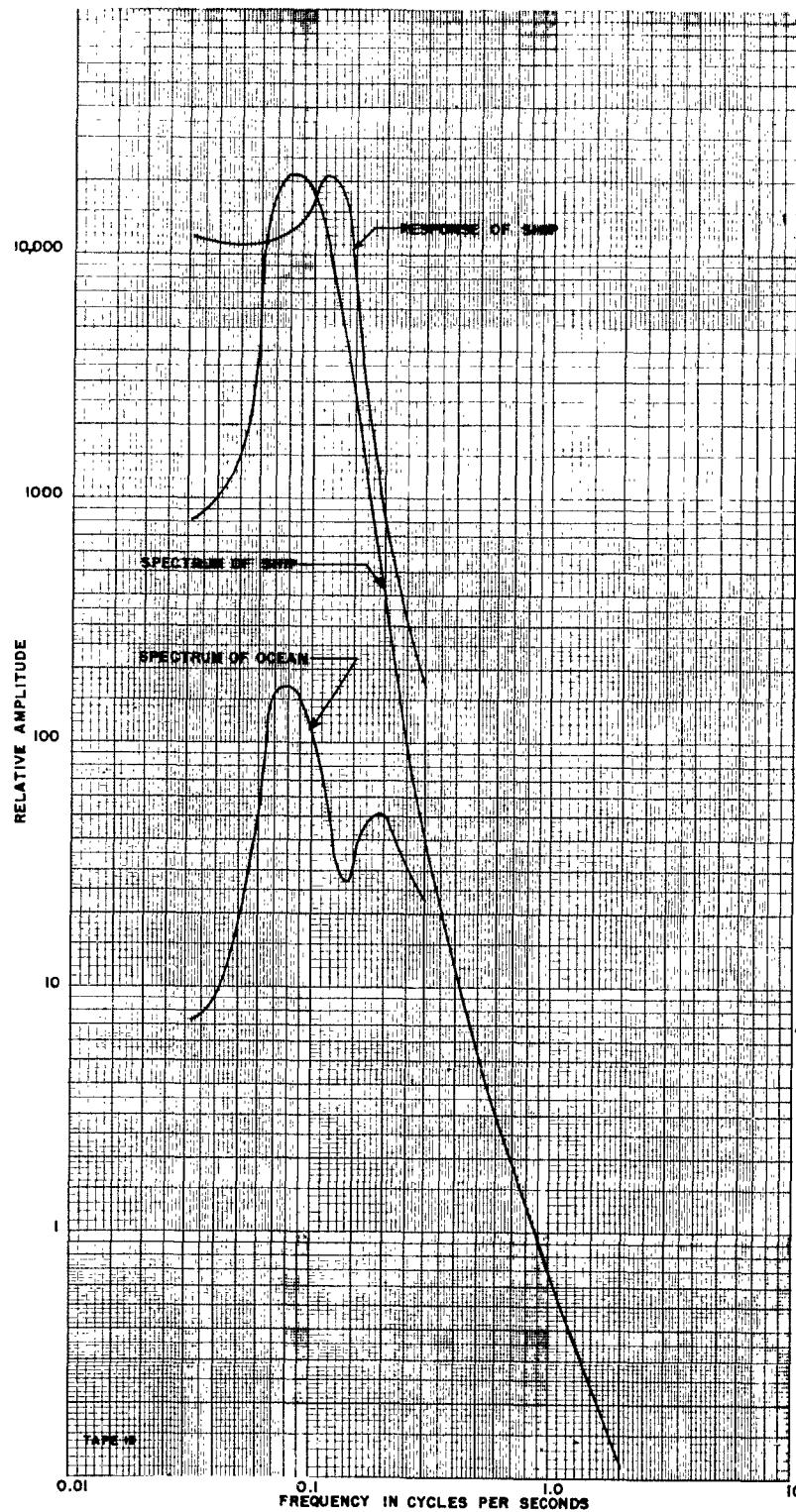


Figure 55. Spectrum of Ship Compared to Transfer Function of Ship

Two accelerometers were mounted in the model, one forward, one aft. The outputs were fed directly to a Sanborn four-channel pen recorder. The natural period of the model was determined from the graphical record of acceleration which resulted when the bow of the model was allowed to drop after being elevated by a string as shown in Figure 56. The natural period, determined by averaging the results of several drops, was found to be 8.33 seconds. (This figure and all others in this chapter, except when noted, is presented full scale rather than model scale).

In addition, the model was towed through waves whose amplitude was constant but whose frequency was varied for each run. The results were corrected for small variations in the model towing speed. The accelerometers were connected as shown in Figure 57, thus the recorded signal was identically pitch acceleration. The response curve plotted in Figure 58 was obtained by graphical integration of the pitch-acceleration spectrum obtained from these tests, and shows the response of the ship to waves of constant amplitude but different frequencies.

The second series of tests, which were performed solely by the David Taylor Model Basin, consisted of repeating the towing tests but at speeds of both 20 and 30 knots. Figure 59 presents the principal results of these tests in condensed form. The maximum acceleration (peak to peak) at the bow is plotted as a function of the frequency of encounter. An interesting result of this study is the shift of the encounter frequency at which maximum acceleration occurs at the different towing speeds.

Figures 60 and 61 show the variations in acceleration plotted as functions of the frequency of encounter. The wave length in feet is indicated for each plotted point. The forward acceleration is the same as that shown in Figure 59.

An interesting sidelight is to assume that the transfer function determined in the Model Basin is the transfer function of the ship, and that the spectra determined from shipboard measurements are correct. On the basis of these assumptions the spectrum of the ocean may be inferred. An example is shown in Figure 55. The spectrum of the ocean is obtained by graphically subtracting the transfer function of the ship from the measured response of the ship. On logarithmic paper this corresponds to a division.

To date it has not been possible to obtain accurate spectra of surface disturbances except for limited cases (such as shallow water) due to the difficulties of measurement. Possibly the method of determining ocean spectra outlined above could be developed into a useful oceanographic tool besides supplying urgently needed information for the current problem.

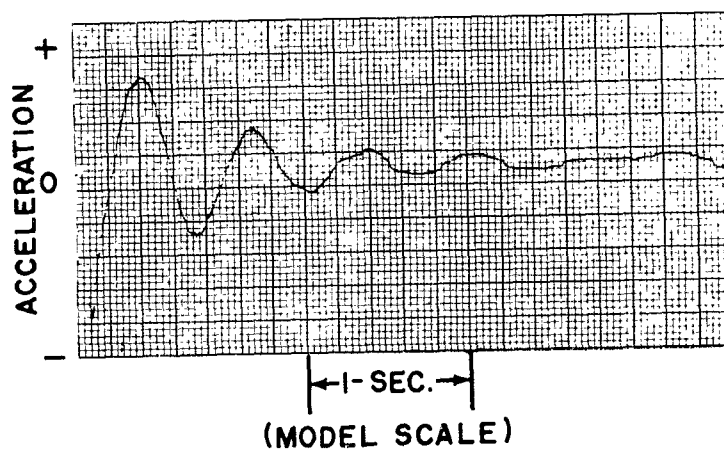
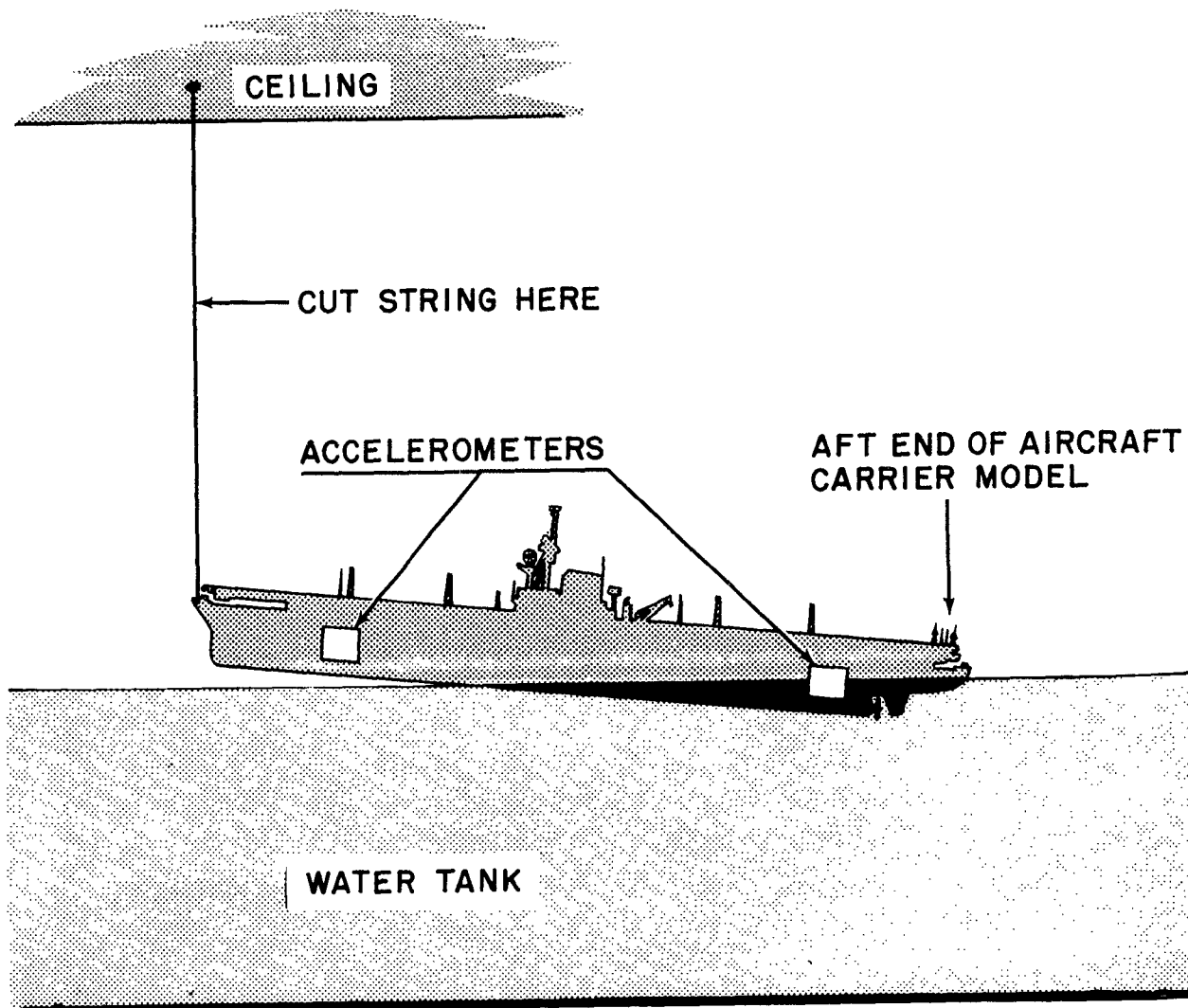


Figure 56. Determination of Natural Period of Ship

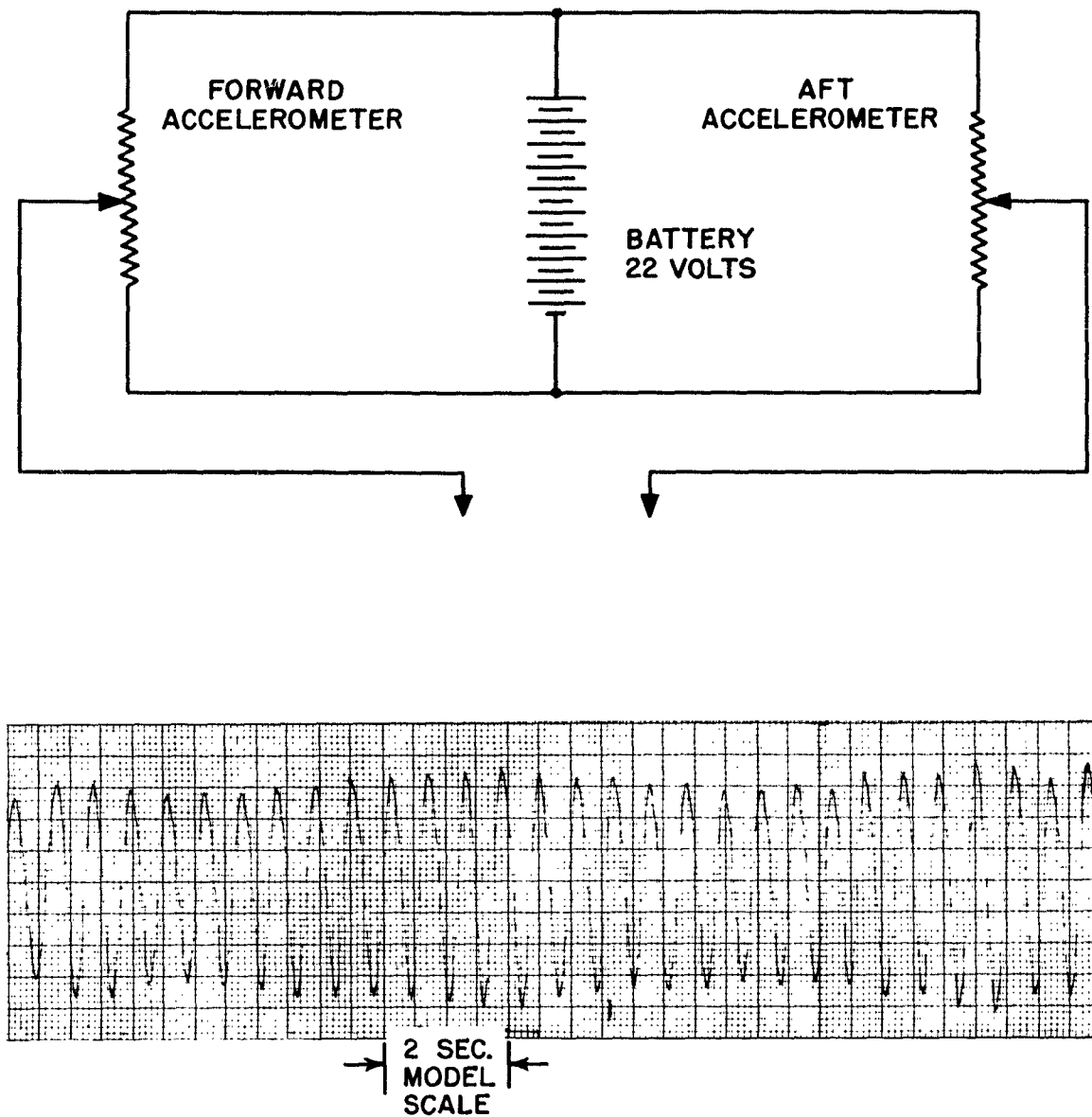


Figure 57. Accelerometer Connections and Typical Record from Towing Tests

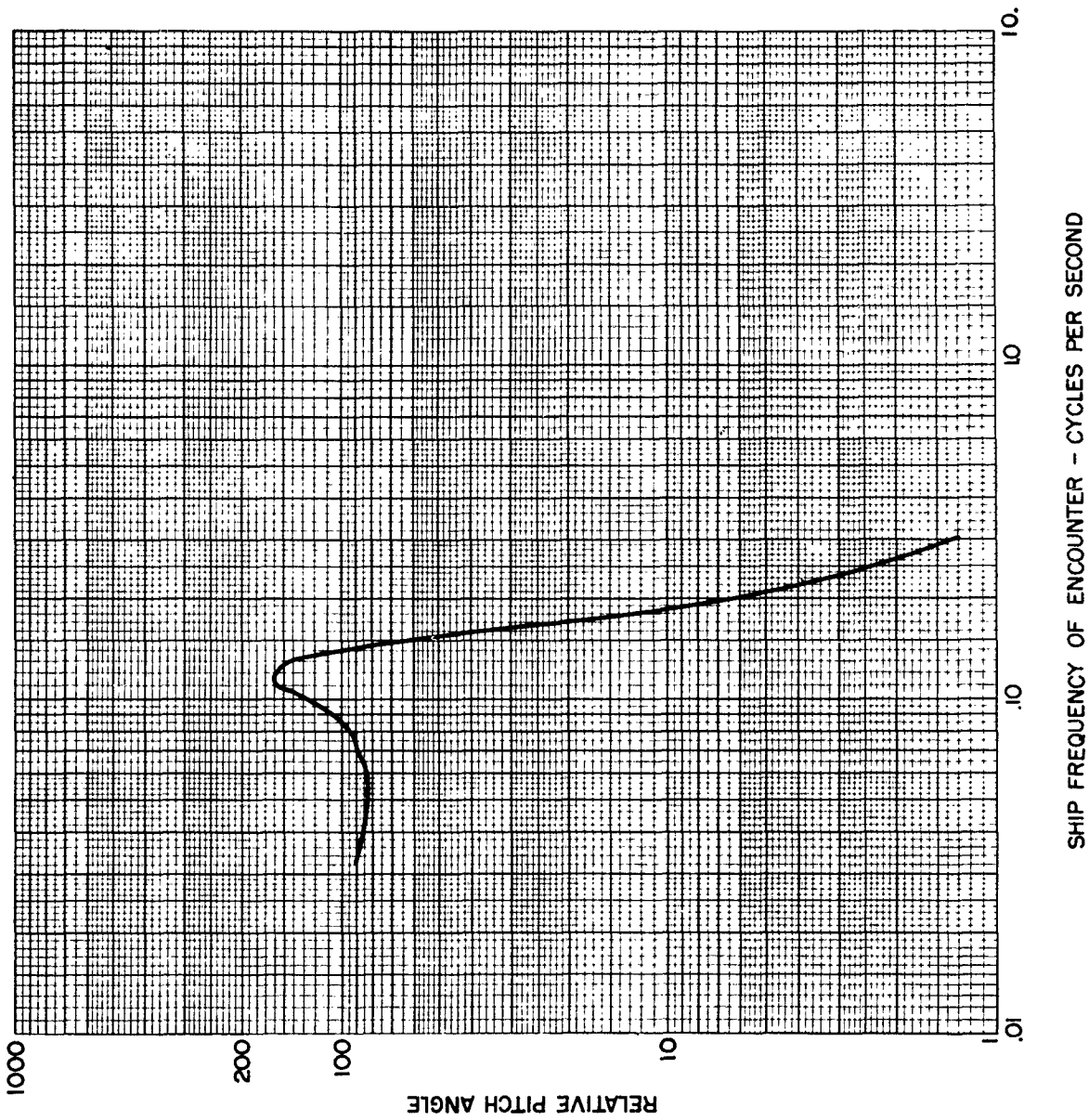


Figure 58. Response of USS Coral Sea, Determined by Model Tests

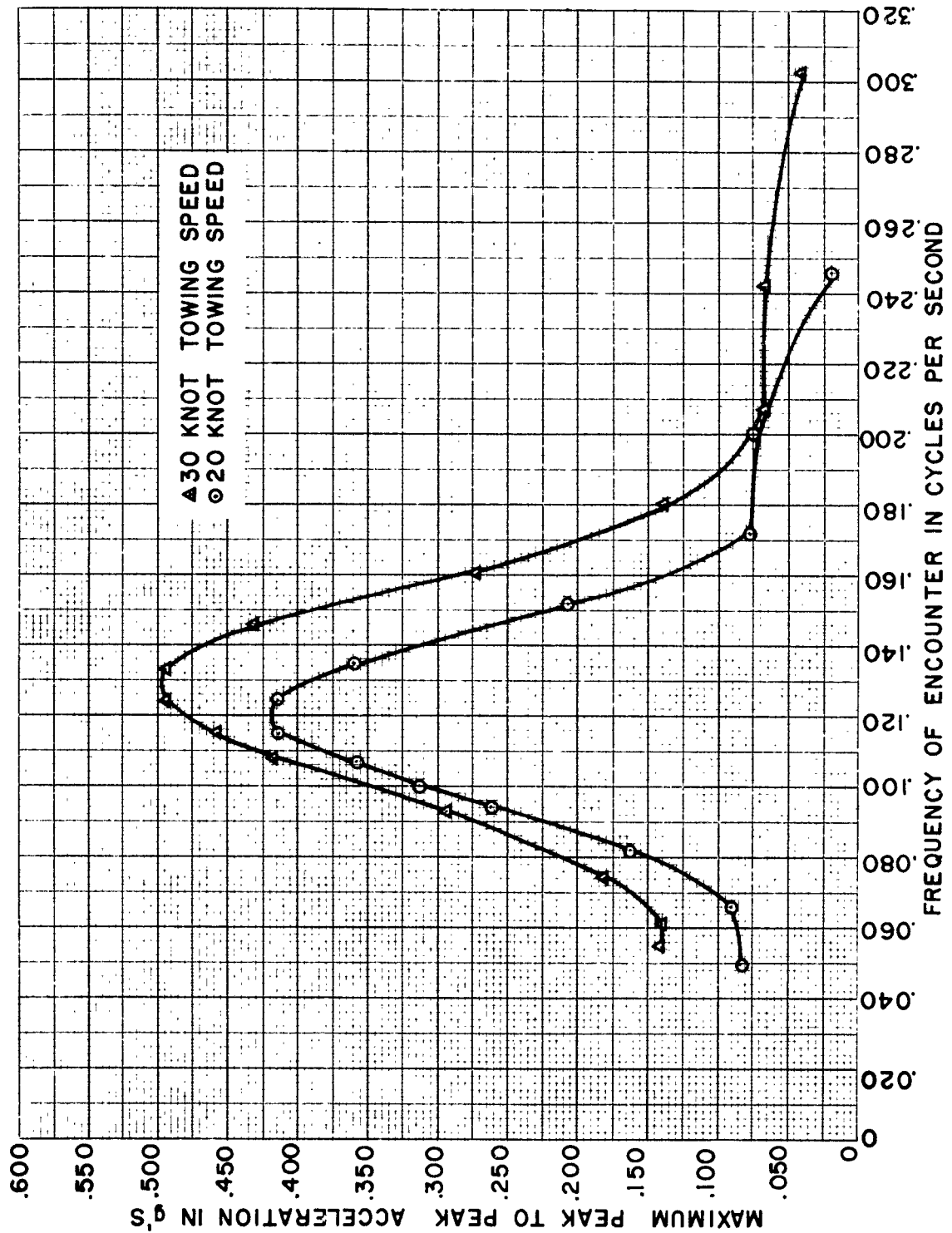


Figure 59. Maximum Forward Acceleration as a Function of Frequency of Encounter

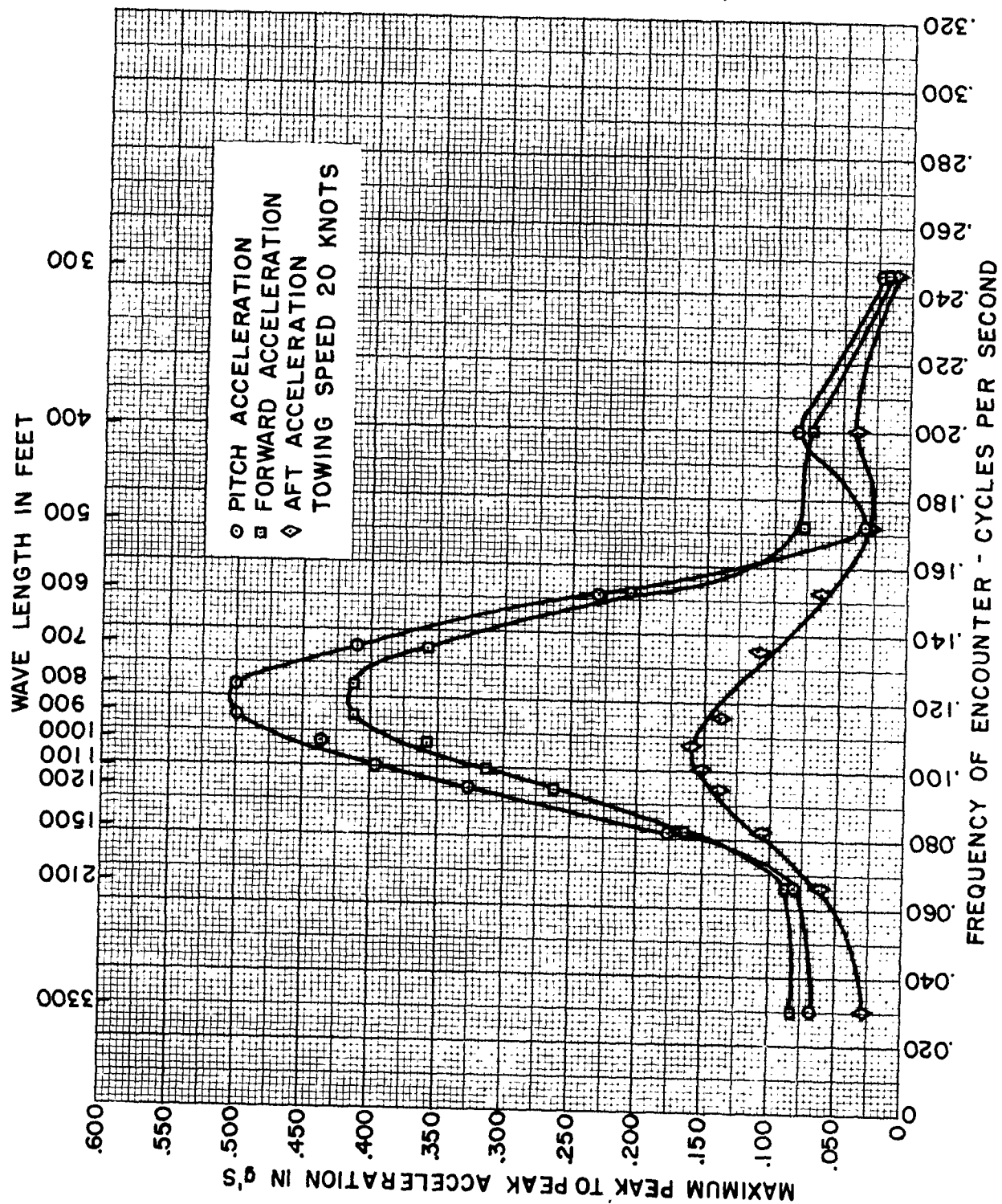


Figure 60. Results of Model-Towing Test

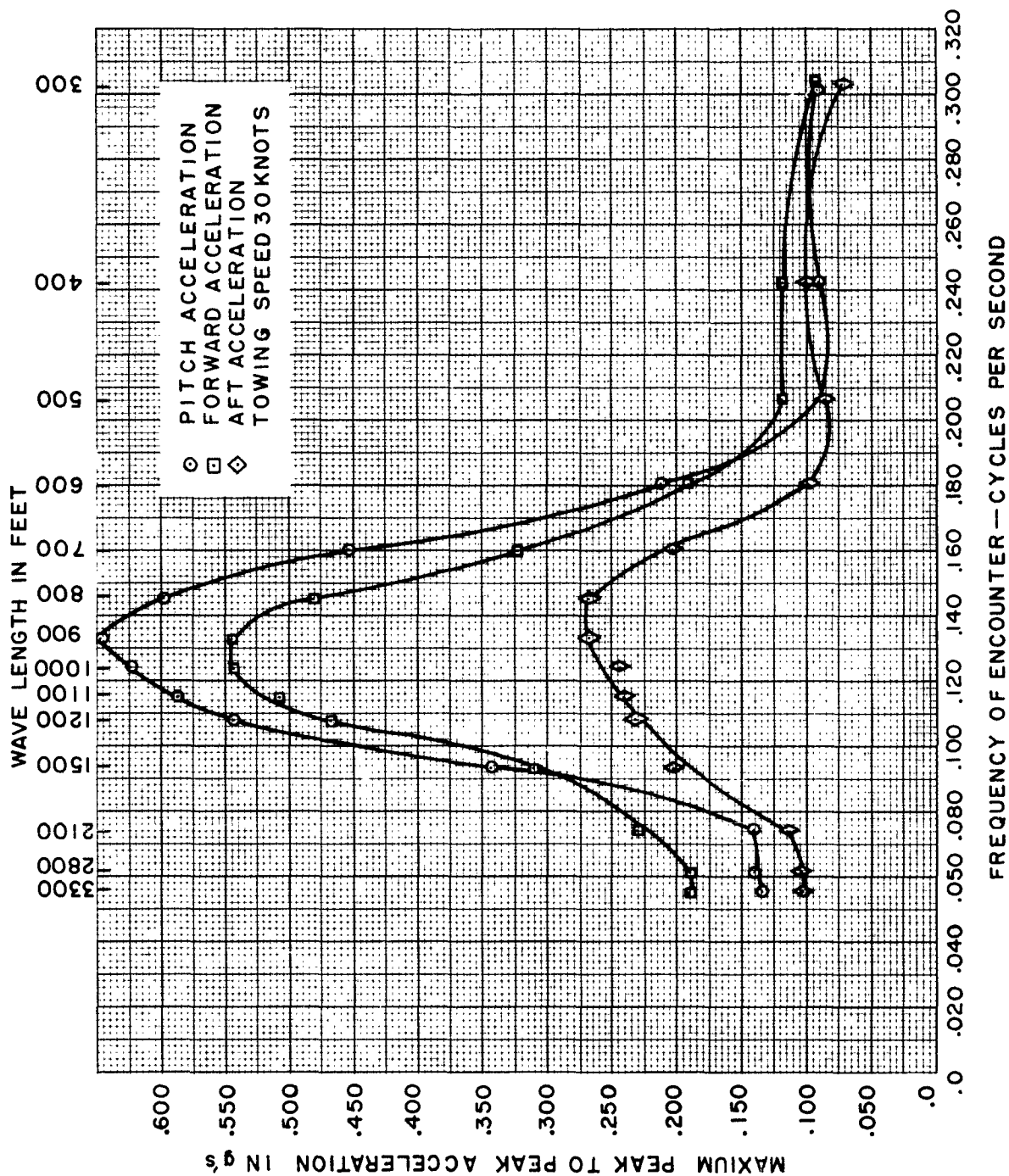


Figure 61. Results of Model-Towing Test

Looking back to the curves in the last section showing pitching period vs period of encounter, it is easy to see that the assumptions made at that time were entirely warranted. From Figure 62 it is apparent that the ship responds to excitation of any frequency. Reference to the response characteristics, Figure 58, however, shows that the response drops very sharply (over 30 db in the first octave) for frequencies higher than the peak corresponding to the natural period. It is not hard to see that if the spectrum of the ocean contained frequency components at or close to the frequency at which the peak of the response curve occurs, the response of the ship to higher frequency components, even though of possibly greater amplitude, would be very small. The response does not decrease nearly as precipitously for frequencies lower than the peak, however, and it would be expected that pitching periods longer than the natural period of the ship would occur. This is shown to be the case in the period-of-encounter curves presented in the last section.

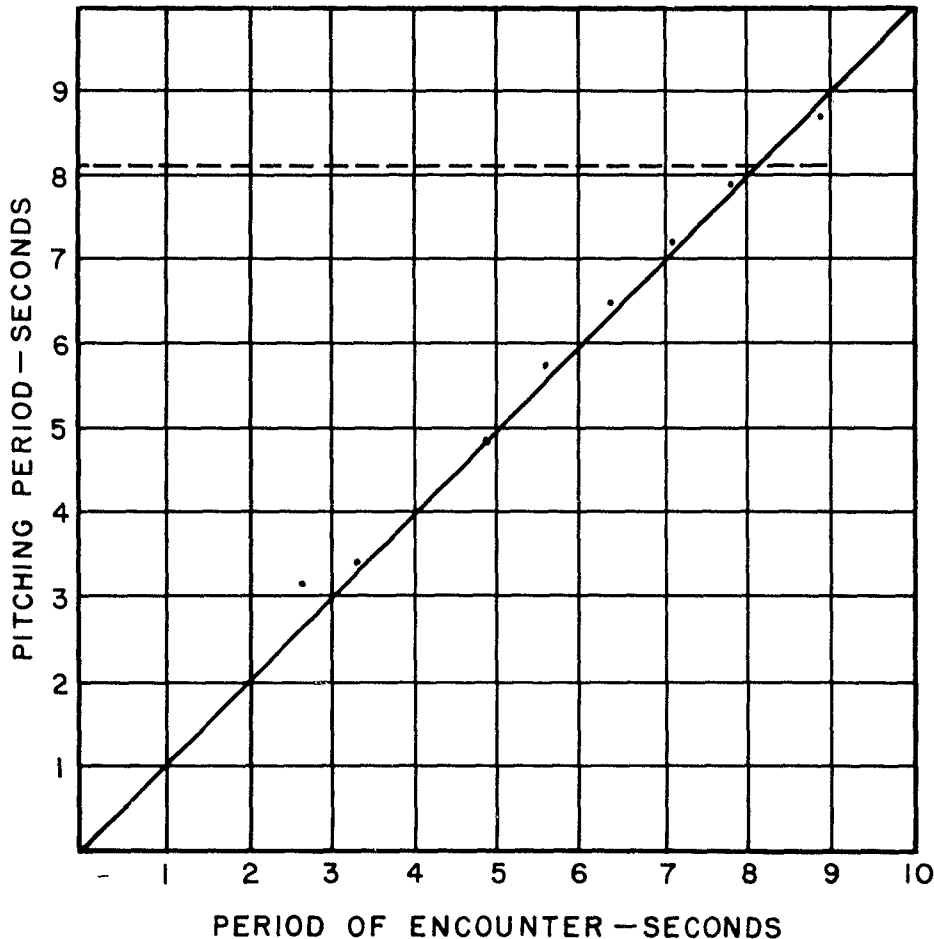


Figure 62. Pitching Period Versus Period of Encounter

There is still one verification which remains. If it should happen that the spectrum of the ocean contained no components of appreciable amplitude in the neighborhood of the peak response of the ship, but contained sizeable components of higher frequency, the ship would be expected to respond at a period shorter than the natural period. Although this situation may be synthesized in a model basin it has not been observed at sea during the current project. Oceanographic data can perhaps supply the answer. Intuitively, it seems doubtful that such a situation would arise.

In the course of these model basin studies it has frequently been necessary to convert between wave length, period, and velocity. Relations between these three quantities were given in the preceding section but the curve shown in Figure 63 is a much more convenient method.

Another convenience which finds frequent utilization is the set of curves in Figure 64. These curves, based on the approximation that the motion is sinusoidal, give the displacement in feet of any point on the ship when the period of the motion and the instantaneous peak acceleration of the point in question are known.

The question of how closely model-basin phenomena duplicate actual real-scale phenomena has been intentionally avoided as there already exists copious literature on the subject. Before closing the subject of model-basin studies, however, it might be interesting to give a short description of the scaling process.

The linear reduction used in the studies recounted in this chapter was 150. Thus a ship 968 feet long is represented by a model about 6-1/2 feet long. Time is scaled down by a factor which is the square root of the linear scale factor, in this case 12.25. The advantage of this relation between the scale factors for length and time arises from the use of accelerometers. Since the dimensions of acceleration are length divided by time squared, the scale factors in numerator and denominator cancel and the acceleration recorded is the same in either ship or model scale.

As an example of the scaling process the linear coordinates of Figure 64 would read 0, 0.08, 0.16, 0.24, inches rather than 0, 1, 2, 3, feet if it were numbered in model scale rather than ship scales. The time coordinate would read 0, 0.0816, 0.1633, 0.2447 seconds, rather than 0, 1, 2, 3, seconds. The curves for different values of acceleration, however, would remain unchanged.

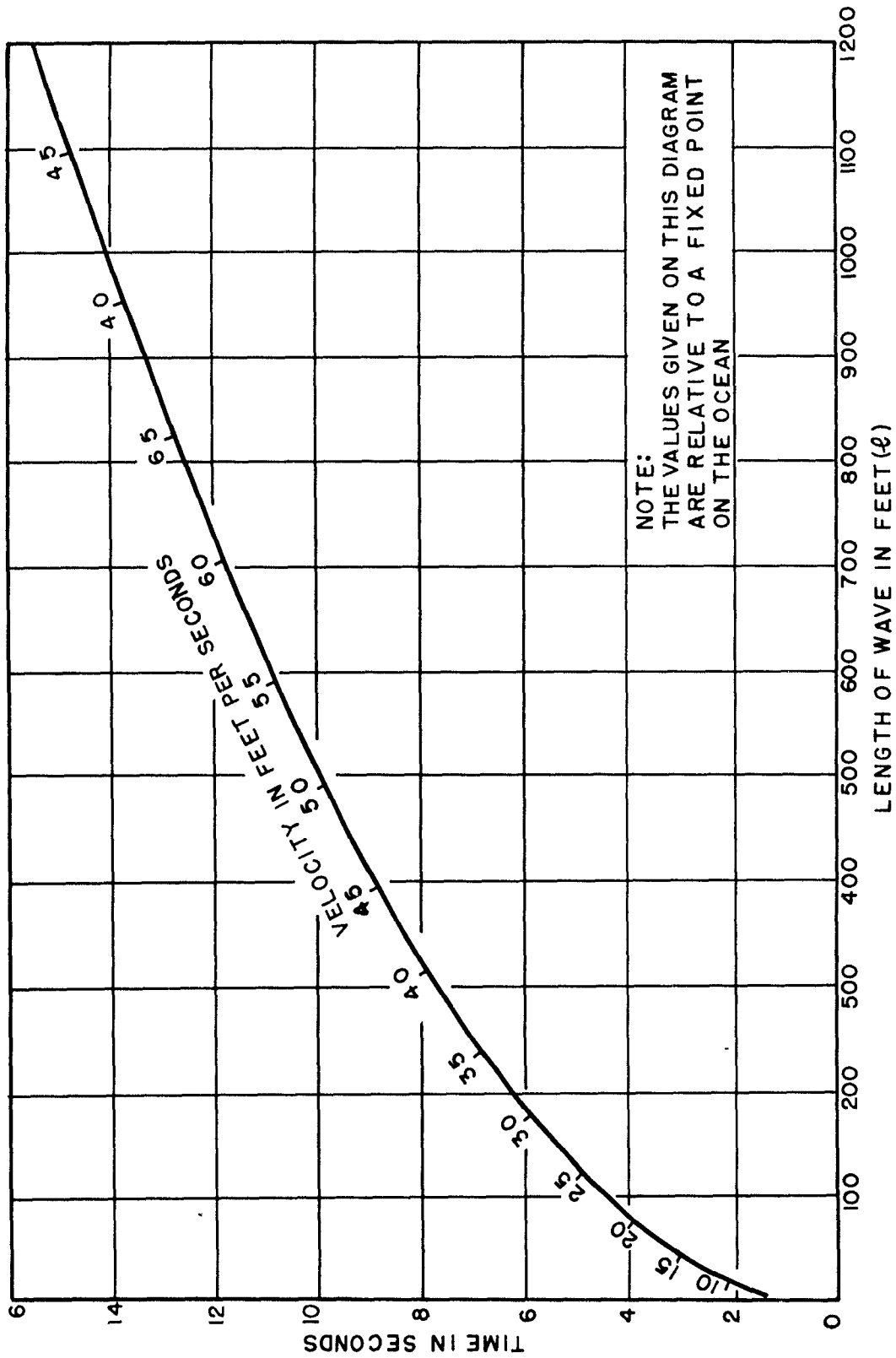


Figure 63. Relation of Wave Length, Period, and Velocity

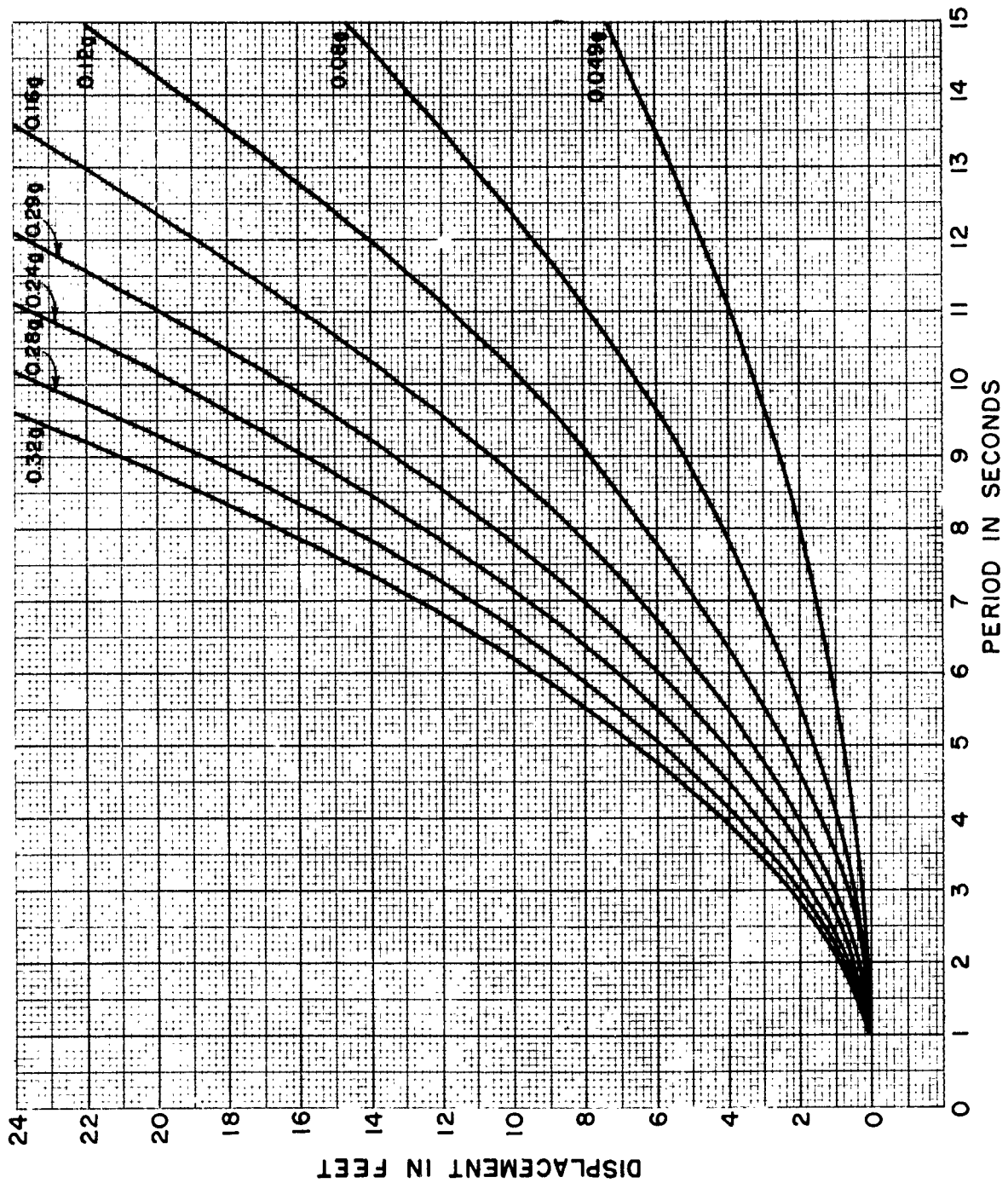


Figure 64. Conversion From Acceleration to Displacement

section IX vibration and slam

The preceding section demonstrated that the most refined pitch spectra which had been obtained were reasonable, but still contaminated by noise. The present section deals with the causes and possible amplitudes of a portion of this contamination.

Previously, in this report, the motion of the ship has been discussed under the tacit assumption that the ship was a rigid body. This point is convenient but is untenable in a detailed analysis. A ship vibrates continuously at many different frequencies. When these vibrations occur at the location of sensing instruments, and with frequencies which are within the sensitive range of these instruments, contamination of the information-signal results. Because the inputs to the predictor will be derived from instruments which are sensitive to these vibrations, the causes and characteristics are of considerable interest.

The amplitude of the vibration depends on many factors. The principal ones are the magnitude of the driving force, the point of applied force, etc. The forces which excite the vibrations may be divided into two groups, internal and external. The most important internal excitation is the main propulsion machinery including the shafts and screws; the principal external excitation results from wave and surface-disturbance action against the hull. Both sources of excitation are undoubtedly present at all times but by far the most important, on the basis of present information, is a special case of the latter called "slam".

In a moderate or rougher sea, the ship occasionally experiences a violent shock accompanied by sudden severe vibrations which gradually decay. The amplitude of the vertical vibrations at the forward accelerometer location of the U.S.S. Oriskany reached a maximum of about 6-1/2 inches and the measured accelerations ranged up to 0.5 g --- both values being peak-to-peak. This phenomenon is termed "slam" and is

associated with the vibration of the entire ship, at its fundamental and associated modes. This vibration, not unlike that of a flexible beam, is excited by interaction between the hull and the supporting medium. These slam vibrations are the primary cause of the peaks occurring at 0.87 cps and 1.67 cps on the pitch-acceleration spectra presented in Section VII. These peaks were faired in on the pitch spectra as they do not describe the motions of the ship but rather, the motions within the ship. It is worth noting that these peaks do not appear on the transfer function of the ship (Figure 58) determined in the Model Basin, possibly because the model, being wood, is highly damped internally.

It has been said frequently that the first step towards understanding something is to measure it. Whether or not this is generally true, in the case of the slam phenomenon the first step was one of measurement; in particular, measurement of the principal frequencies of vibration. The fundamental mode and the second mode were determined while making the spectra of pitch acceleration presented earlier. Since the vibration at the fundamental mode consists of one standing wave, the accelerations at the ends of the ship are of the same sign at any instant. Partial cancellation takes place in the subtraction process by which pitch acceleration is obtained. Complete cancellation does not occur for many reasons, principally because the accelerometers were not symmetrically placed with respect to the nodes. At the second, and other even-order modes, the accelerations are of opposite sign and hence are additive. For these reasons, the relative size of the two peaks on the pitch-acceleration spectra has no quantitative meaning, although the results could be interpreted if the position of the nodes were known.

Because the scatter of points becomes large at a frequency just higher than the peak representing the second mode, it was not considered worthwhile to extend the spectra to higher frequencies, even though it was expected that the peaks for some of the higher modes would be readily identifiable. An alternate, and considerably faster procedure, was used to identify the frequencies of the third and fourth modes.

Pitch acceleration was taken as the input to three filters, such as had been used previously, having slightly different center frequencies. The outputs were connected to three channels of a Sanborn four-channel pen recorder. Pitch acceleration was fed into the fourth channel. Simultaneously, forward acceleration from the same tape was used as the input to a similar system of filters and another pen recorder. Thus, the even-order modes could be determined from pitch acceleration and the odd-order modes could be determined from linear acceleration. Only a small portion of the tape, one which contained two very pronounced slams was used. The frequencies of the modes were identified by visual inspection of the Sanborn records.

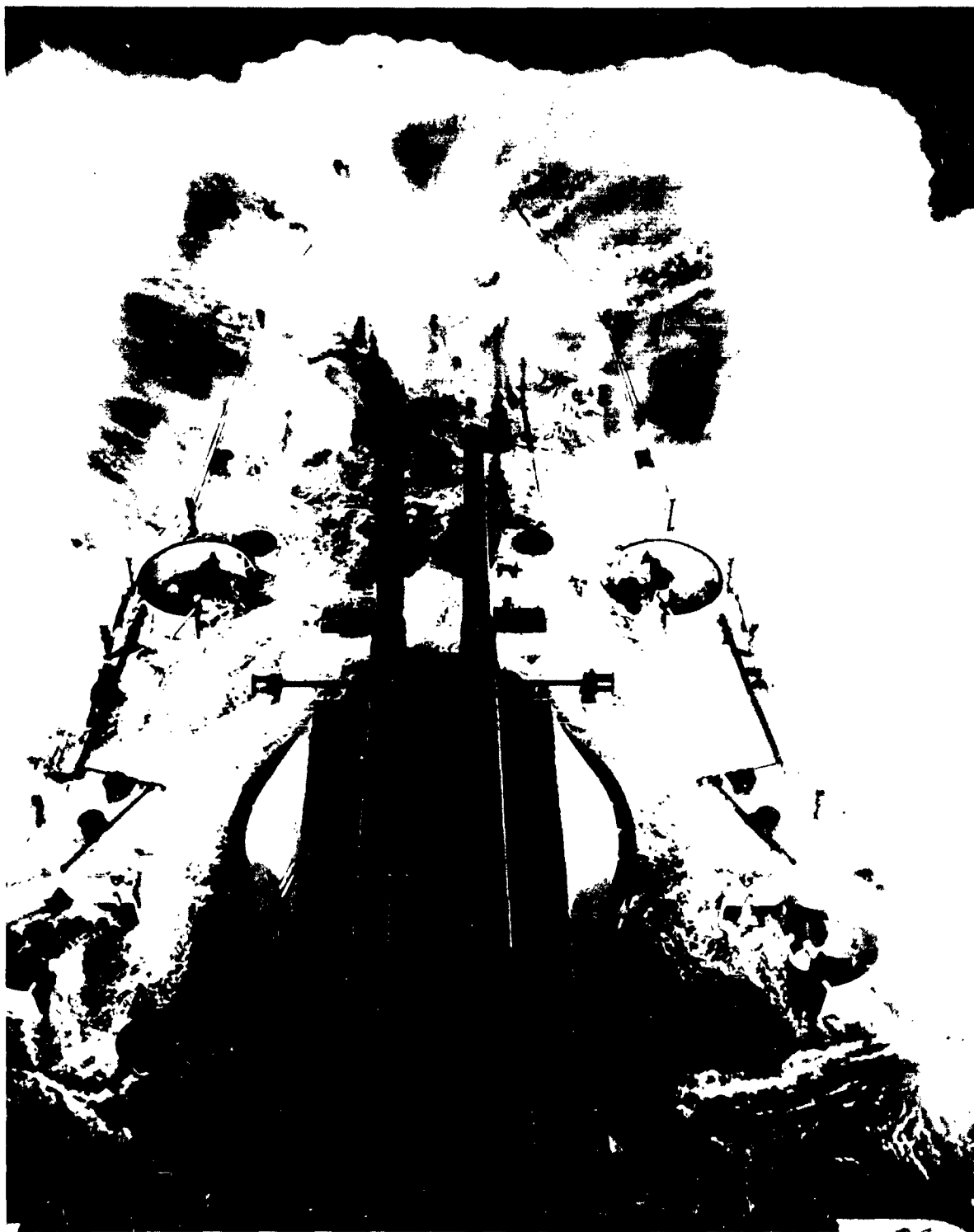


Figure 65. Slam!



Figure 66. Another Example of Slam - USS Saratoga

Table 4 gives the measured values of the frequencies of the first four modes, compared with the values computed and measured by R. T. McGoldrick, of the David W. Taylor Model Basin.

Table 4
Frequencies of Principal Modes

Mode	MEASURED Frequency cps	By R. T. McGoldrick	
		COMPUTED cps	MEASURED cps
Fundamental	0.87	0.785	.87
2nd	1.67	1.53	
3rd	2.56	2.42	2.6
4th	3.60	3.32	3.6

The amplitudes of the accelerations at the different modes vary from one slam to another. In some instances, the first mode vibration will be relatively small and the second mode vibration will be very pronounced; in other cases the situation is just reversed. It is believed that the location of the area at which the slam impact occurs is responsible for this. The ship does not respond at a certain mode if the impact occurs at a node for that mode. Figure 67 shows several typical examples.

The investigation of the slam phenomenon, subsequent to the determination of the frequencies of the first four vertical modes, continued with visual inspection of graphic records made directly from the recorded tapes on a Sanborn four-channel pen recorder. Neglecting possible difference in the response time of the instruments used aboard ship to sense and transmit the data, the vertical coordinates on the paper are considered to be time interval marks. Thus, it is possible to examine in detail the accelerations at the various accelerometer locations and the pitch and roll at the same instant. Two such records, both made during conditions of heavy slamming, are shown in Figures 68 and 69.

From examination of such records it appears that slam occurs a small fraction of a cycle before the lowest point reached by the bow during the pitching cycle. In some instances of slam the pitching amplitude is large just prior to the slam and small immediately after-

wards. Other instances show the pitching amplitudes to vary in just the opposite manner. On still other occasions there appears to be little change in the pitching amplitude either before or after the slam. (Figure 71.)

Further examination of the pitch record shows that slams are usually associated with large pitch amplitudes; however, slams frequently occur when the pitch amplitude is small. To sum up, on the basis of the available data concerning slam, it appears that:

1. Slam occurs a small fraction of a cycle before the ship reaches the lowest point of the pitching cycle.
2. Whether a slam occurs at a given instant (which satisfies (1) above) is independent of the behavior of the ship in pitch over the preceding four or five cycles.
3. The occurrence of a slam does not affect the pitch motion over the subsequent four or five cycles.
4. Increase of the average amplitude of the pitch motion increases the probability of slamming. The probability does not, however, appear to be a linear function of the average amplitude.
5. There is nothing in the preceding statements that is intended to preclude the possibility that an additional, and as yet undiscovered, relation exists between pitch and slam.

Investigation of slam by visual inspection of acceleration records, particularly forward acceleration, presents virtually the same picture that scrutiny of the pitch records did. The slam occurs just before the negative peak of the acceleration cycle. The occurrence of slam does not appear to be dependent on the behavior of the preceding four or five cycles, nor is there a noticeable effect on the subsequent acceleration, except of course, for the presence of the higher frequencies. As with pitch, the probability of slamming appears to increase with an increase of the average amplitude of the forward acceleration.

No correlation has been found between roll and slam. Slams have been detected during all parts of the roll cycle. There does seem to be a slightly greater number of slams occurring at the peak of the roll cycle than at other times. At present not enough data have been analyzed to determine whether or not this is significant.

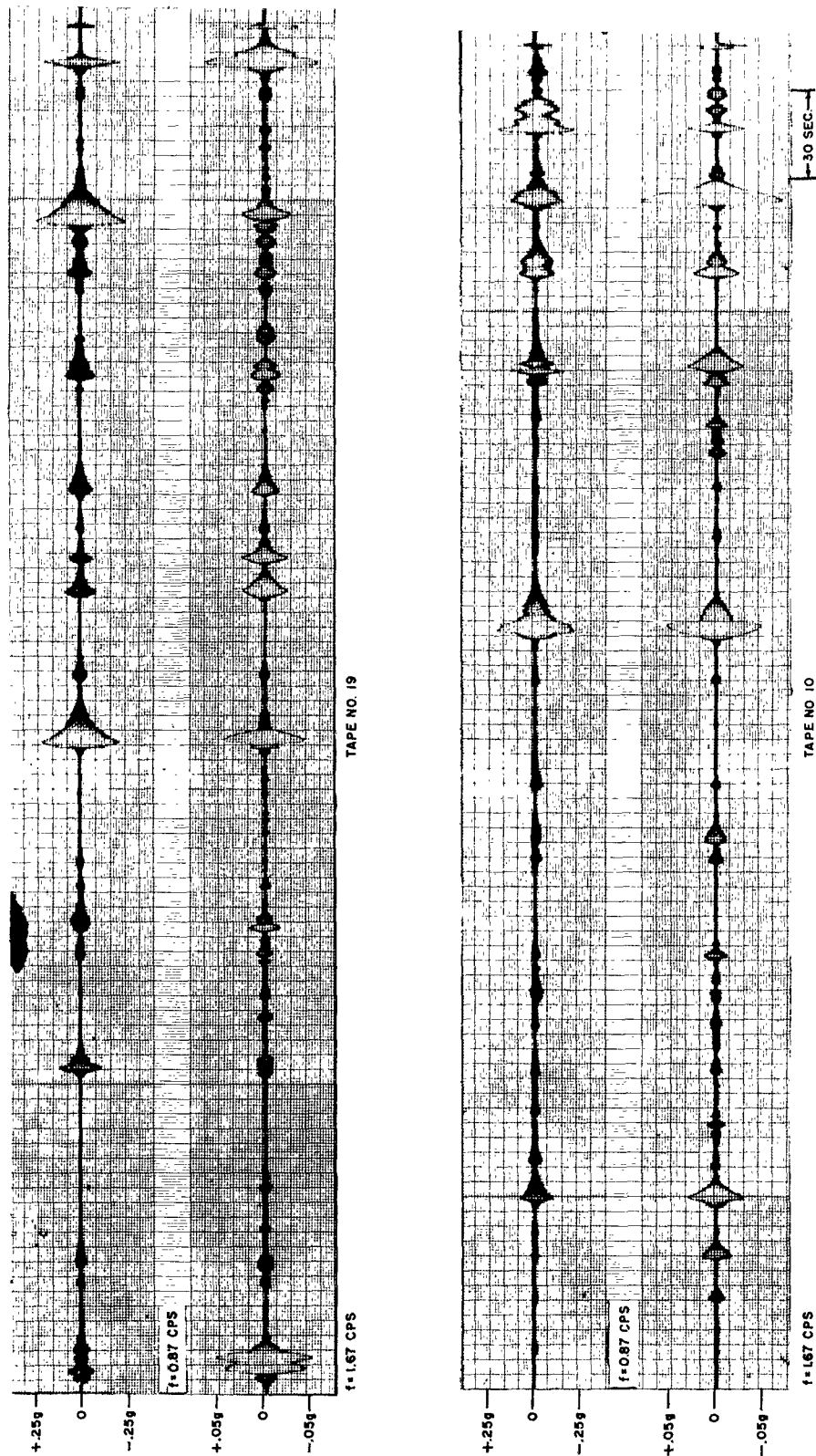
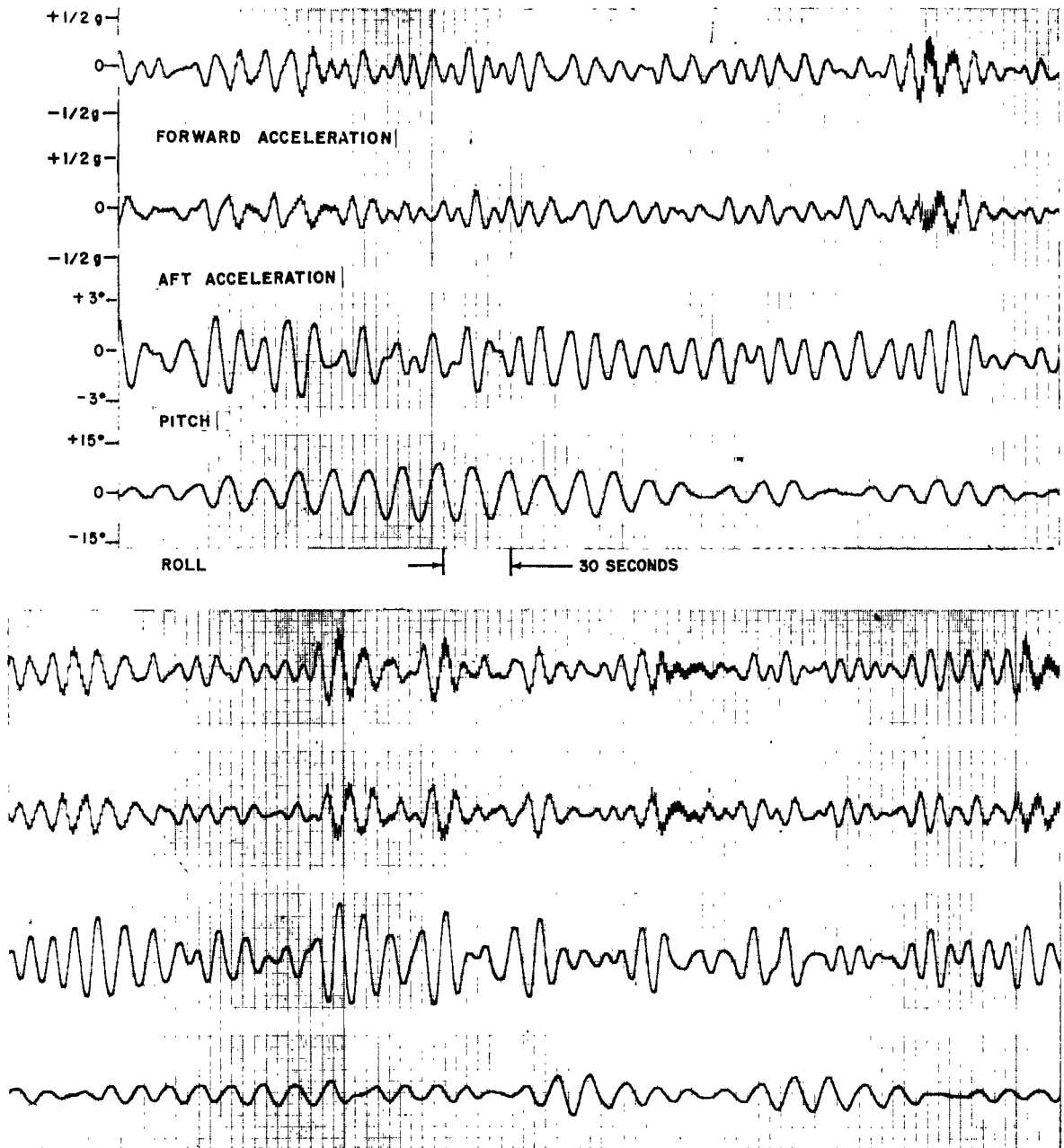
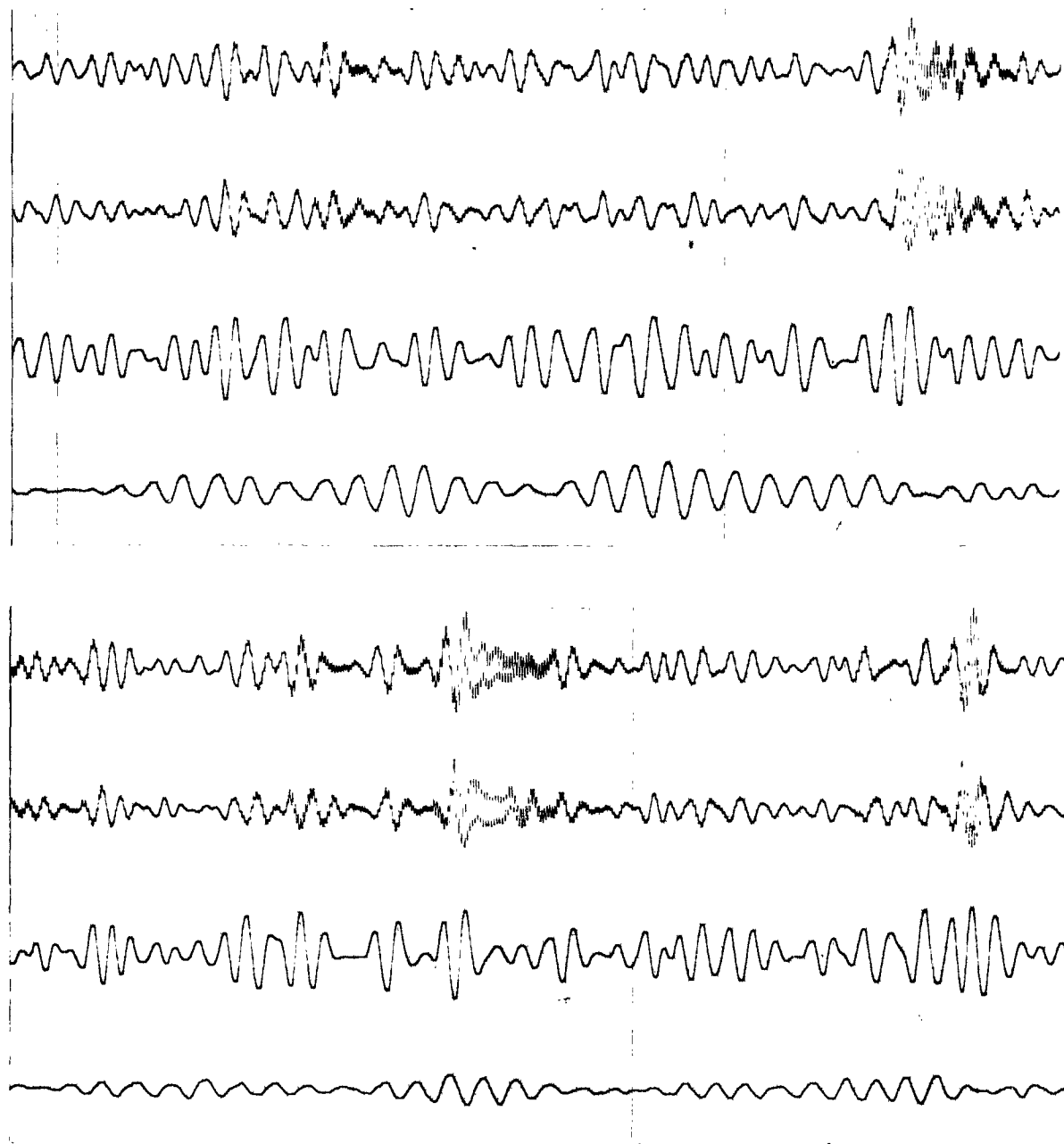


Figure 67. Output of Filters Showing Distribution of Energy Between First and Second Modes



TAPE NO. 19

Figure 68. A Half-Hour Record of the Motion of the USS Oriskany . . .



COURSE 355°
17 KNOTS

WIND 300°
40 KNOTS

WAVES 290°

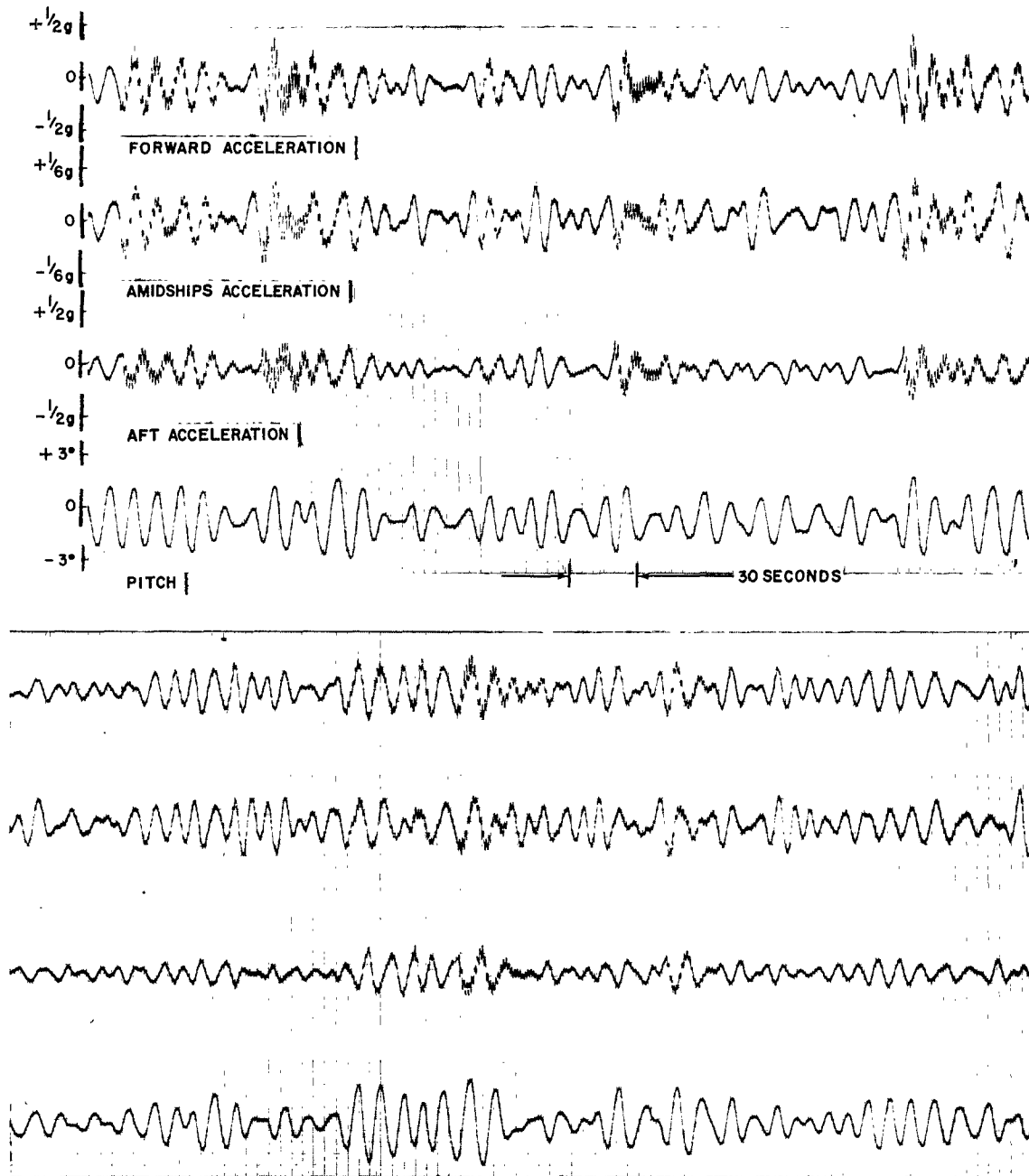
RECORDED OFF CAPE HORN
ON 30 JUNE, 1952

SHIP'S POSITION
55°S 74°W

STORM SEA
20' WAVES 500' LENGTH

STEAMING OPERATIONS

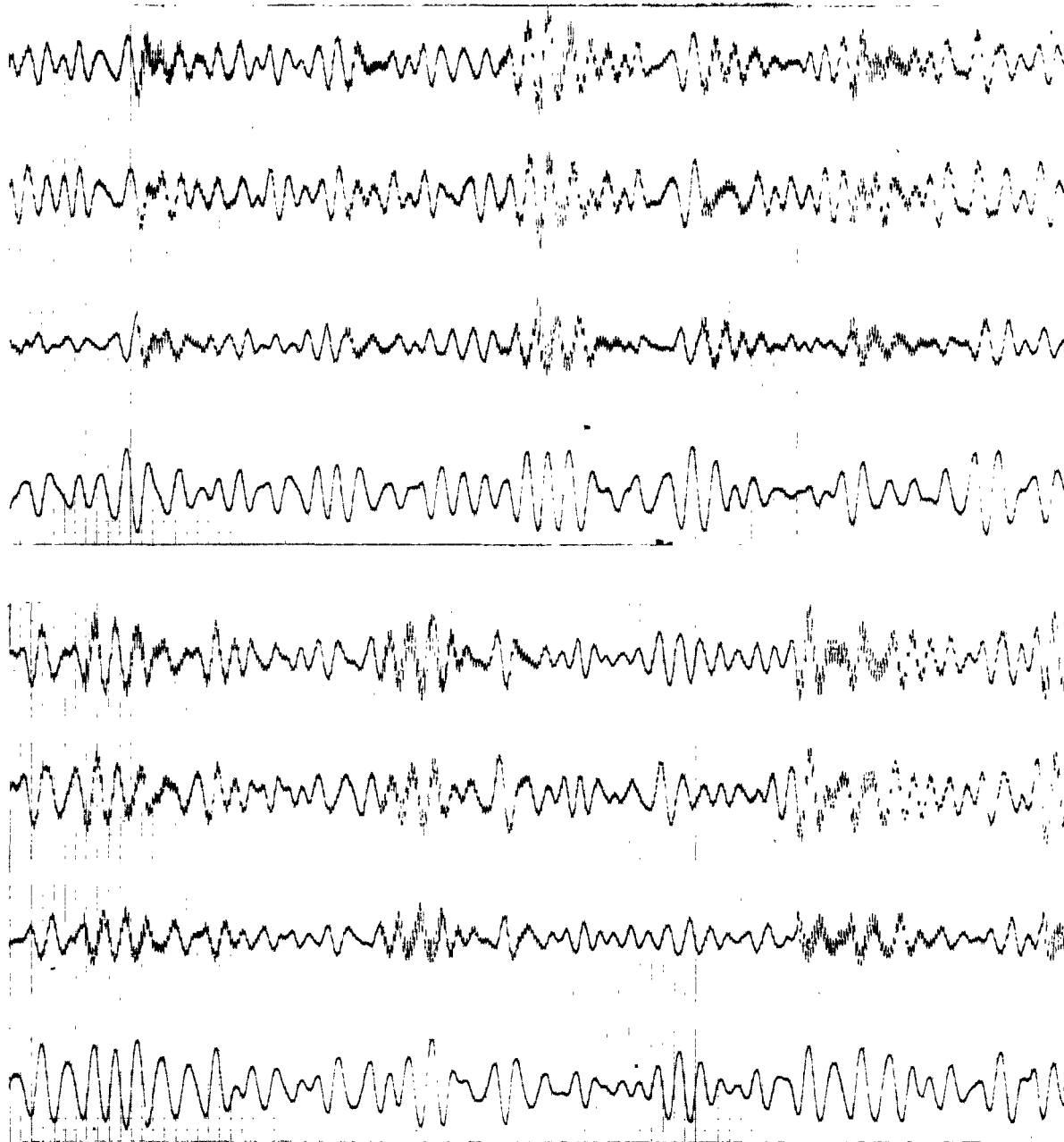
Recorded During a Storm Off Cape Horn



TAPE NO. 20

PITCH AND ACCELERATION
USS ORISKANY CV-34

Figure 69. A Half-Hour Record of the Motion of the USS Oriskany . . .



COURSE 295°
10 KNOTS

WAVES 290°

WIND 300°
40 KNOTS

RECORDED OFF CAPE HORN
ON 30 JUNE, 1952
SHIP'S POSITION
55°S 74°W
STORM SEA
20' WAVES 500' LENGTH
STEAMING OPERATIONS

Recorded During a Storm Off Cape Horn

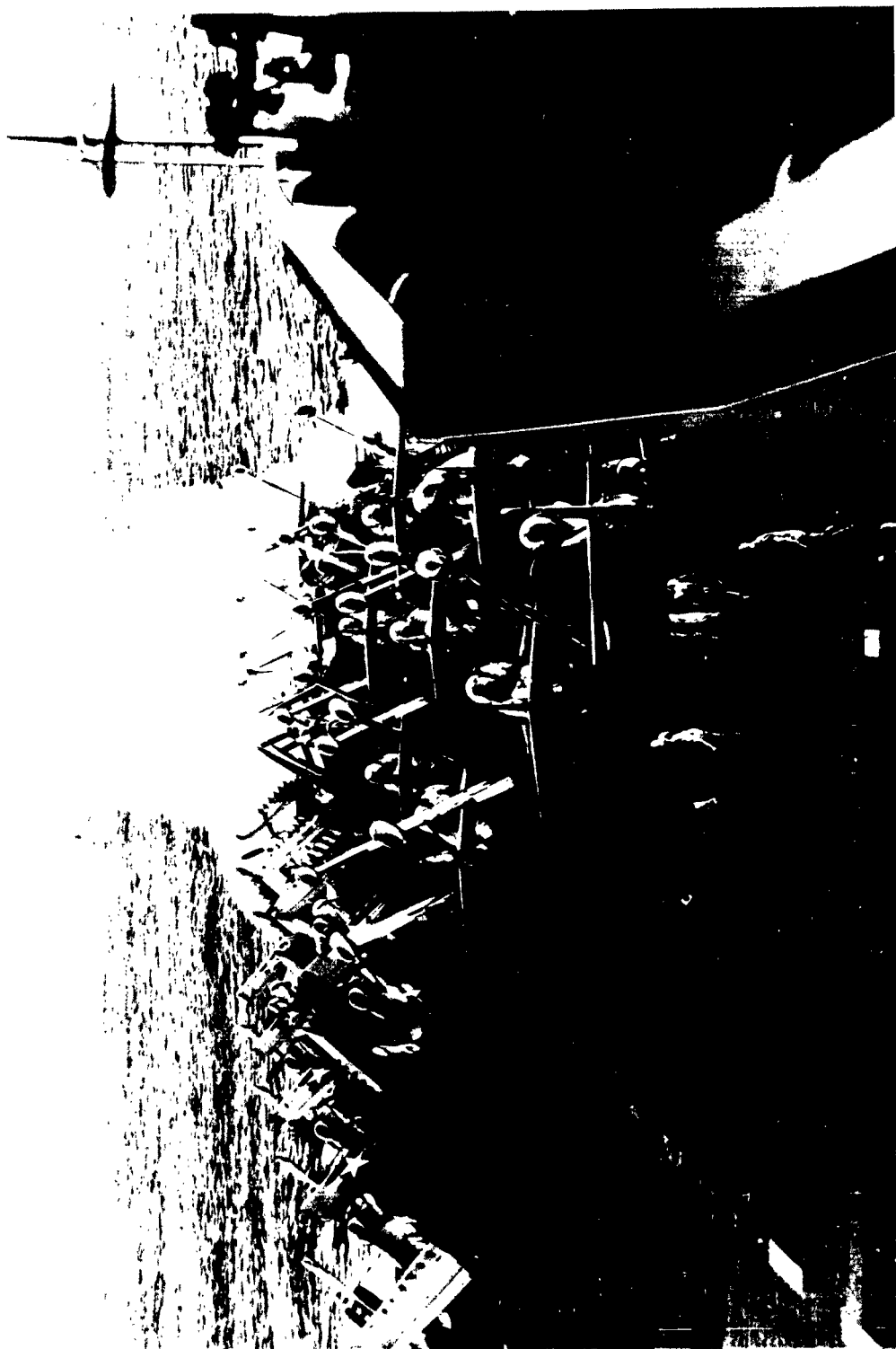


Figure 70. Slam in an Apparently Calm Sea

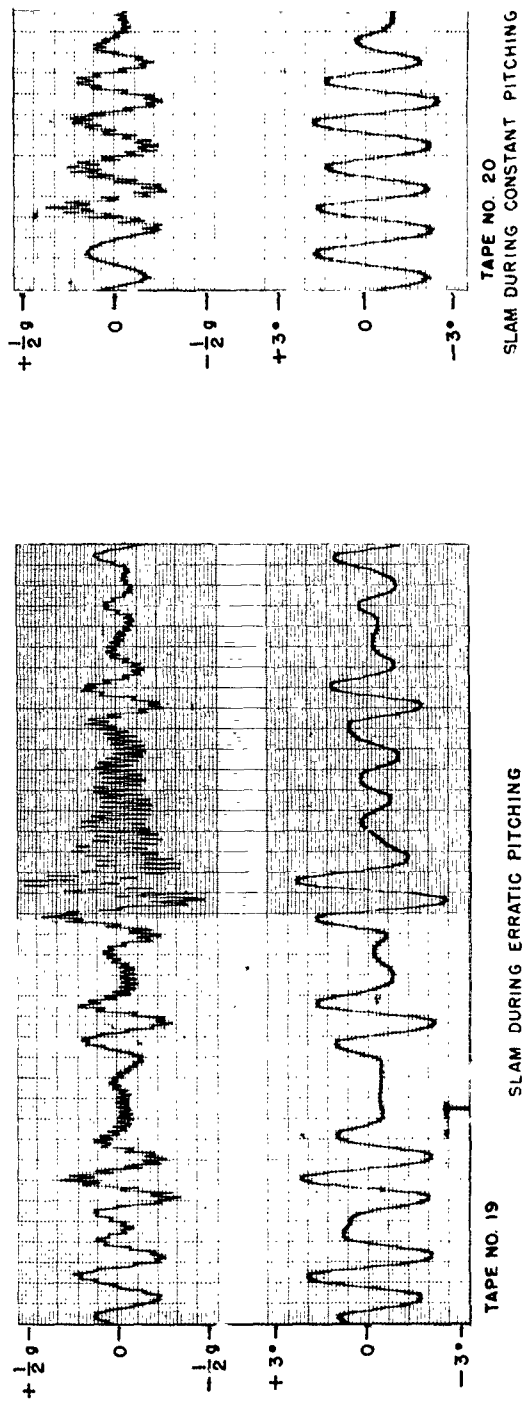
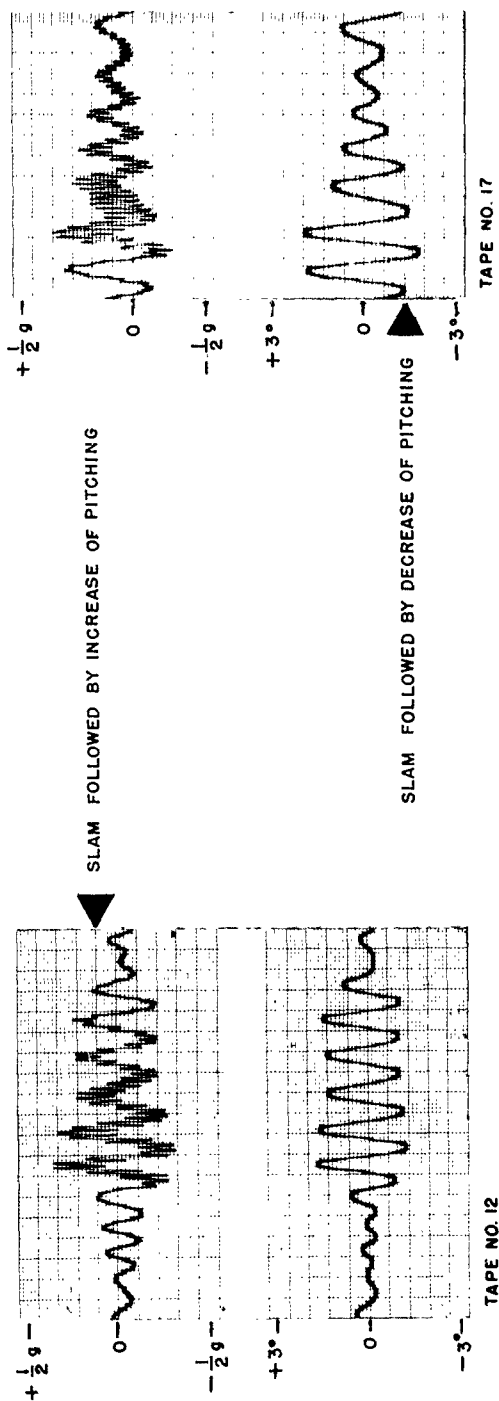
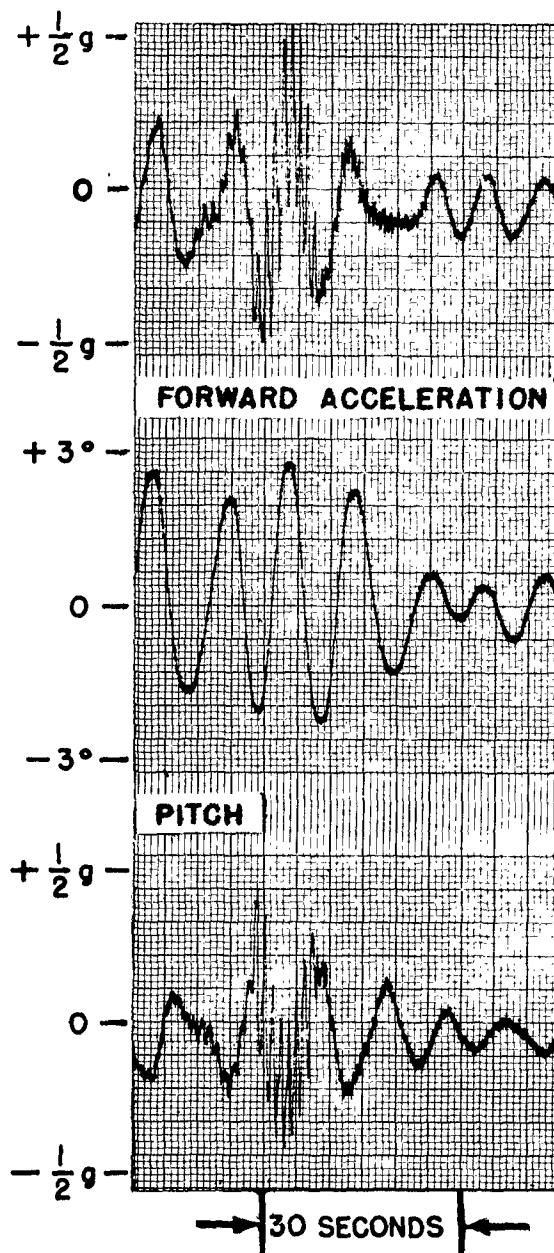


Figure 71. Comparison of Pitch and Acceleration During Slam



TAPE NO. 19

AFT ACCELERATION

Figure 72. Slam Vibrations Damped by Subsequent Slam

One further attempt to gain more information about slam was made. The rectified outputs of two filters having center frequencies of 0.87 cps and 1.67 cps were integrated over the length of each tape. The input signal to both filters, forward acceleration, was also rectified and integrated. Thus, average values of the total acceleration and the components at each of the first two modes were determined. All magnetic tapes recorded on the U.S.S. Oriskany were investigated in this manner. The peak amplitude occurring at each mode on each tape was determined from Sanborn pen recordings.

The results are shown in Figures 73 to 77.

The number beside each point on Figure 73 is the number of the tape from which that point was obtained. The large amount of vibration indicated on tape 23 was due to the fact that it was recorded during a high-speed run when engine and shaft vibrations were much more than normally severe.

The scatter of plotted points is greater than would be expected if due only to equipment inaccuracies. It seems apparent that any results produced by this particular technique will be of a statistical nature. Despite the fact that twenty-seven half hour tapes were used, it is evident that considerable additional data are needed before definite information can be obtained.

The preceding pages have been principally devoted to the techniques and results of an analysis of slams. Although this analysis is far from complete and there is still much to be learned about the slam phenomenon, it is possible to utilize this partially understood phenomenon to obtain other information about the ship, specifically the damping factor which controls the rapidity with which the vibrations decay.

For any damped system exhibiting an exponential decay

$$\frac{a_0}{a_1} = \frac{a_1}{a_2} = \frac{a_2}{a_3} = \dots = \frac{a_{n-1}}{a_n} = \dots = \epsilon^\delta$$

where a_i is the amplitude of the i^{th} cycle, ϵ is the base of the natural system of logarithms and δ is the decrement. The ratio of the amplitude of the initial and n^{th} cycles is given by:

$$\frac{a_0}{a_n} = \epsilon^{n\delta} \quad \text{or} \quad \frac{a_n}{a_0} = \epsilon^{-n\delta}$$

thus, if n is taken as $\frac{1}{\delta}$

$$\frac{a_n}{a_0} = \frac{1}{\epsilon} = .37$$

δ may therefore be determined as the reciprocal of the number of cycles required for the amplitude to decrease to 37% of the initial value. This

may easily be expressed in a form familiar to electronics engineers, since $\delta = \pi/Q$, where Q is comparable to the usual 'quality factor' as applied to tuned circuits.

If the assumption is made that the decay of the slam-induced vibrations is exponential, this analysis may be applied to records of acceleration during slamming to determine the Q of the ship.

It was found convenient to separate the first mode vibrations by means of a band-pass filter. The filter used was narrow enough so that the graphical record of the output was symmetrical about a constant zero axis, but not so narrow that the time for the filter to 'ring out', after a pulse input was applied, was comparable to the decay of a typical slam. Forward acceleration from several tapes containing pronounced slamming was used as the input and the values of δ and Q determined directly from the graphical record of the output. Investigation of 22 separate slams yielded average values of $\delta \approx 0.045$ and $Q \approx 70$.

It is apparent from these results that the hull of the ship is highly underdamped or — in electronics terms — has a high Q . A wooden model of this ship would have a very much smaller Q , that is, it would be considerably overdamped, owing to the difference in nature of wood and steel, and slam vibrations would not be expected. This illustrates the care that must be taken in model-basin work — there are some phenomena that cannot be readily duplicated by wooden models of steel ships.

During the time spent in this work we have formulated certain theories regarding slam. Unfortunately these cannot be verified on the basis of the data available at this time. Moreover, certain of the theories are at considerable variance with some of the ideas of other researchers and it is not deemed advisable to advance them without verification.

As far as the carrier landing problem is concerned, it is apparent that if the inputs to the predictor are obtained from accelerometers, contamination is to be expected, principally at the fundamental frequency of vertical vibration and its associated modes. The vibrations arise from two sources, internal and external. The former is largely a function of the ship's speed, whereas the latter depends on the surface disturbance of the ocean — and probably many other things, such as hull design. It may be possible to minimize, though not to eliminate, the effects of these vibrations by suitable placement of the sensing instruments with respect to the various nodes. Furthermore, it should not be overlooked that there probably exist local vibrations which do not affect the entire ship but nevertheless could prove to be serious sources of contamination.

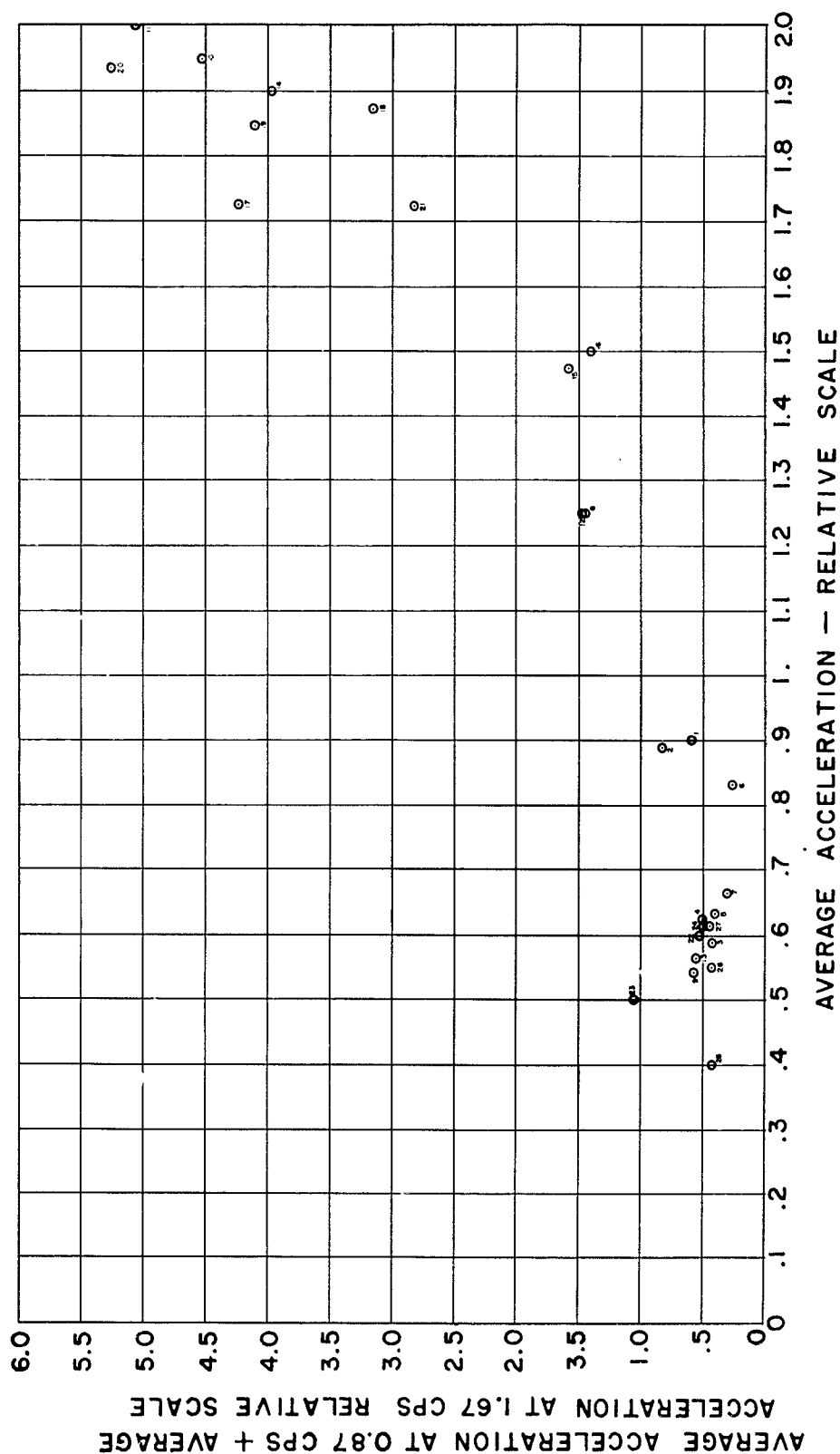


Figure 73. Acceleration at Frequencies of First Two Modes as a Function of Total Acceleration

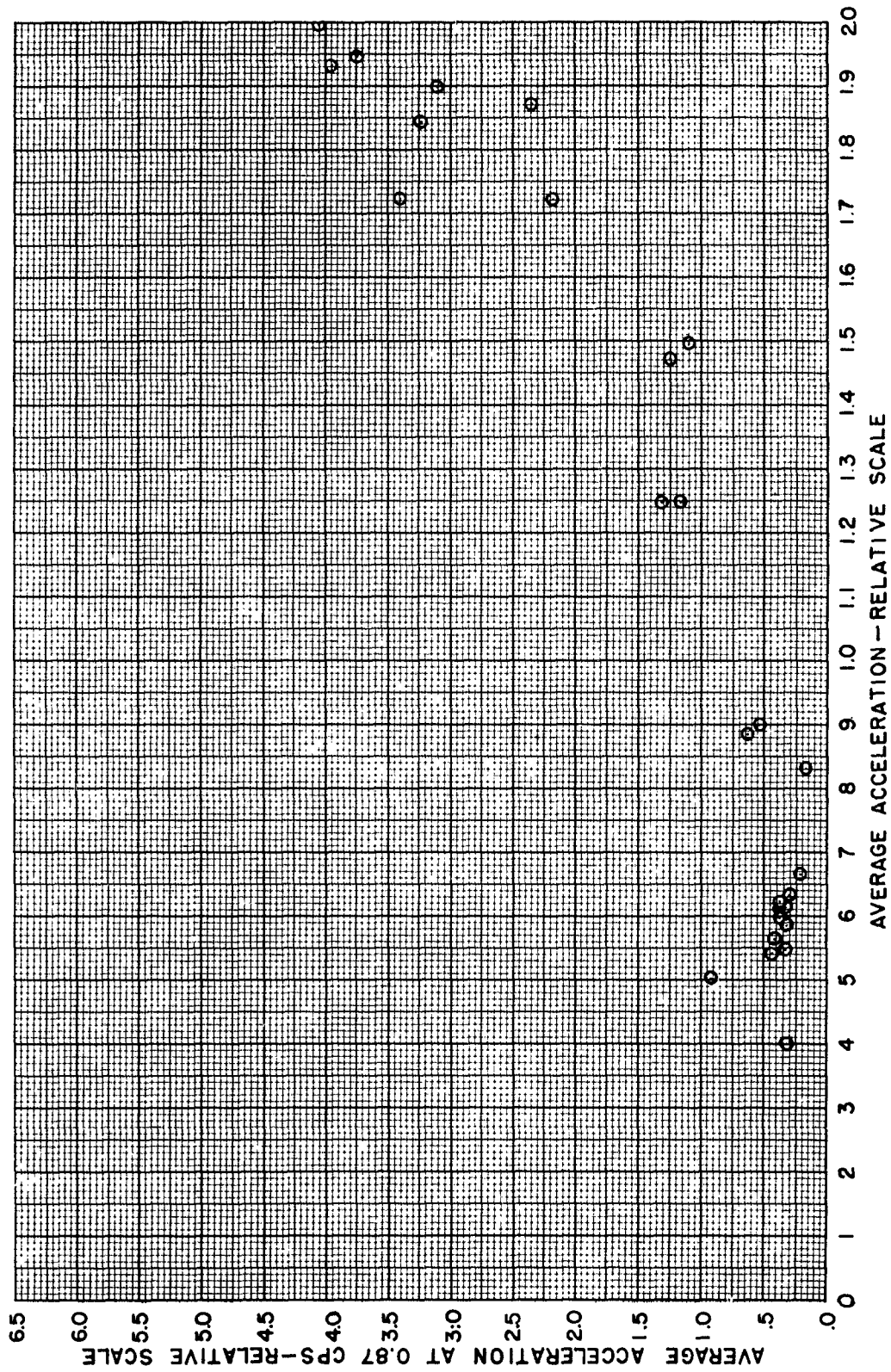


Figure 74. Acceleration at Frequency of First Mode as a Function of Total Acceleration

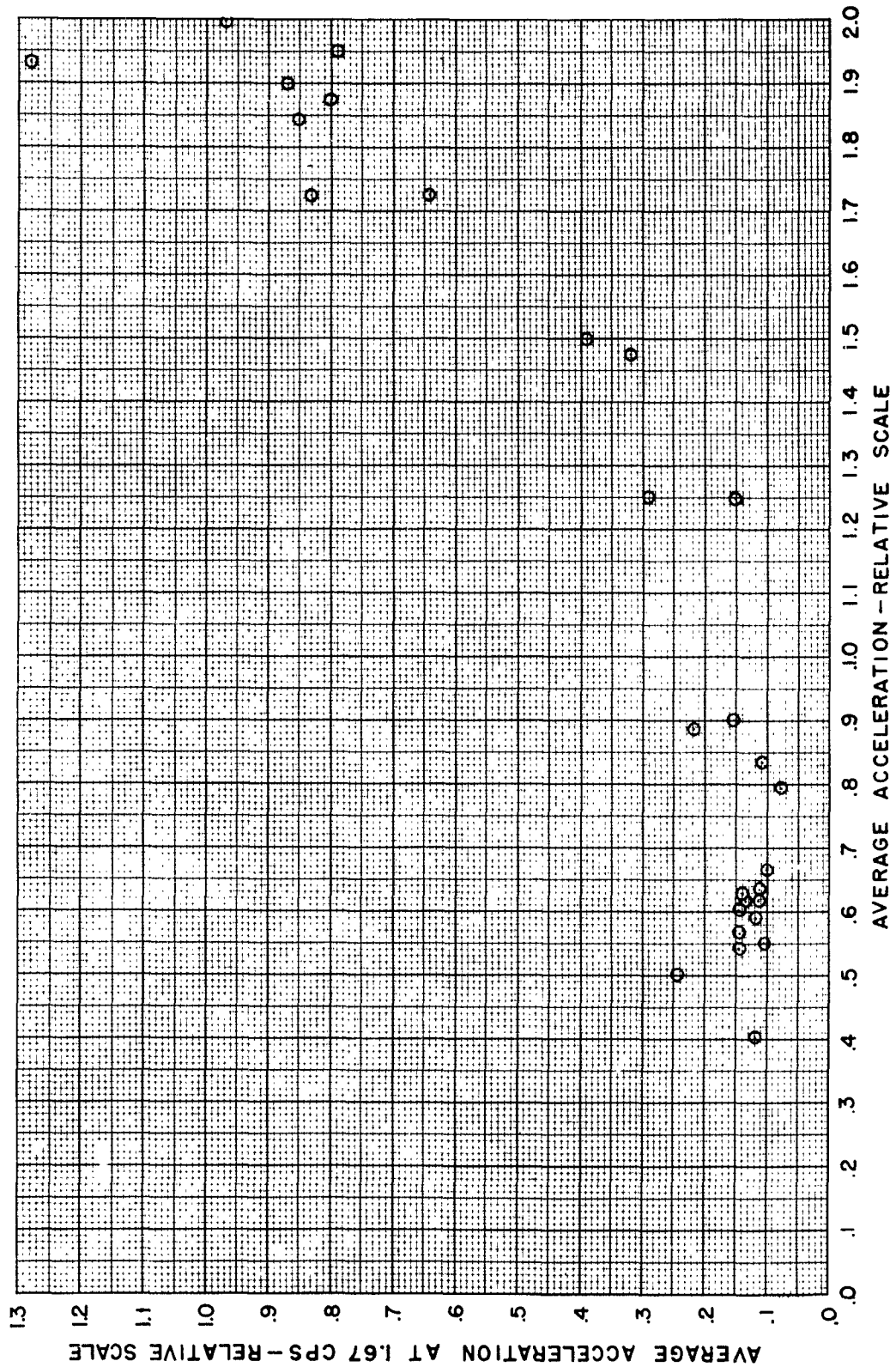


Figure 75. Acceleration at Frequency of Second Mode as a Function of Total Acceleration

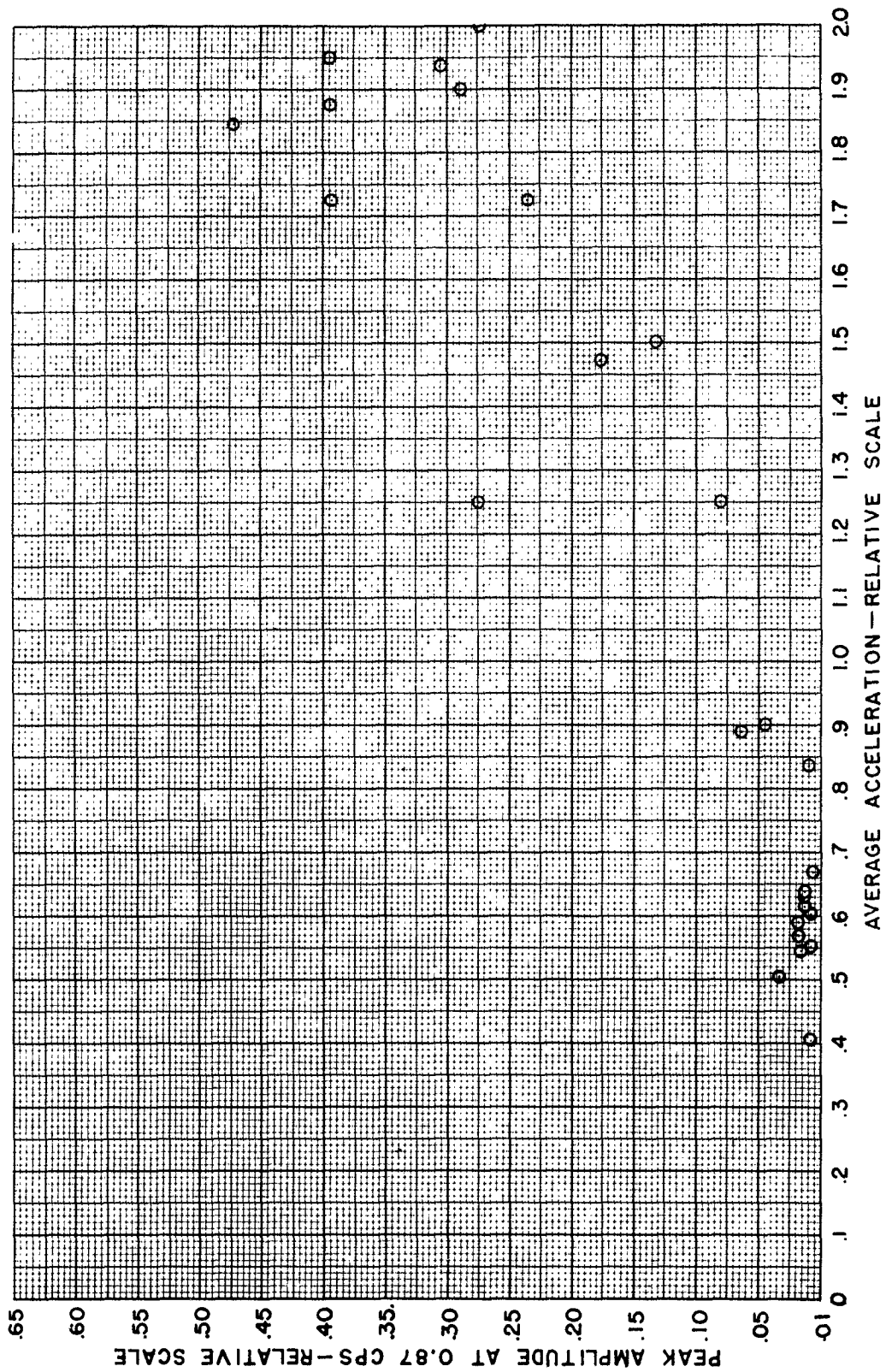


Figure 76. Peak Acceleration at Frequency of First Mode as a Function of Total Acceleration

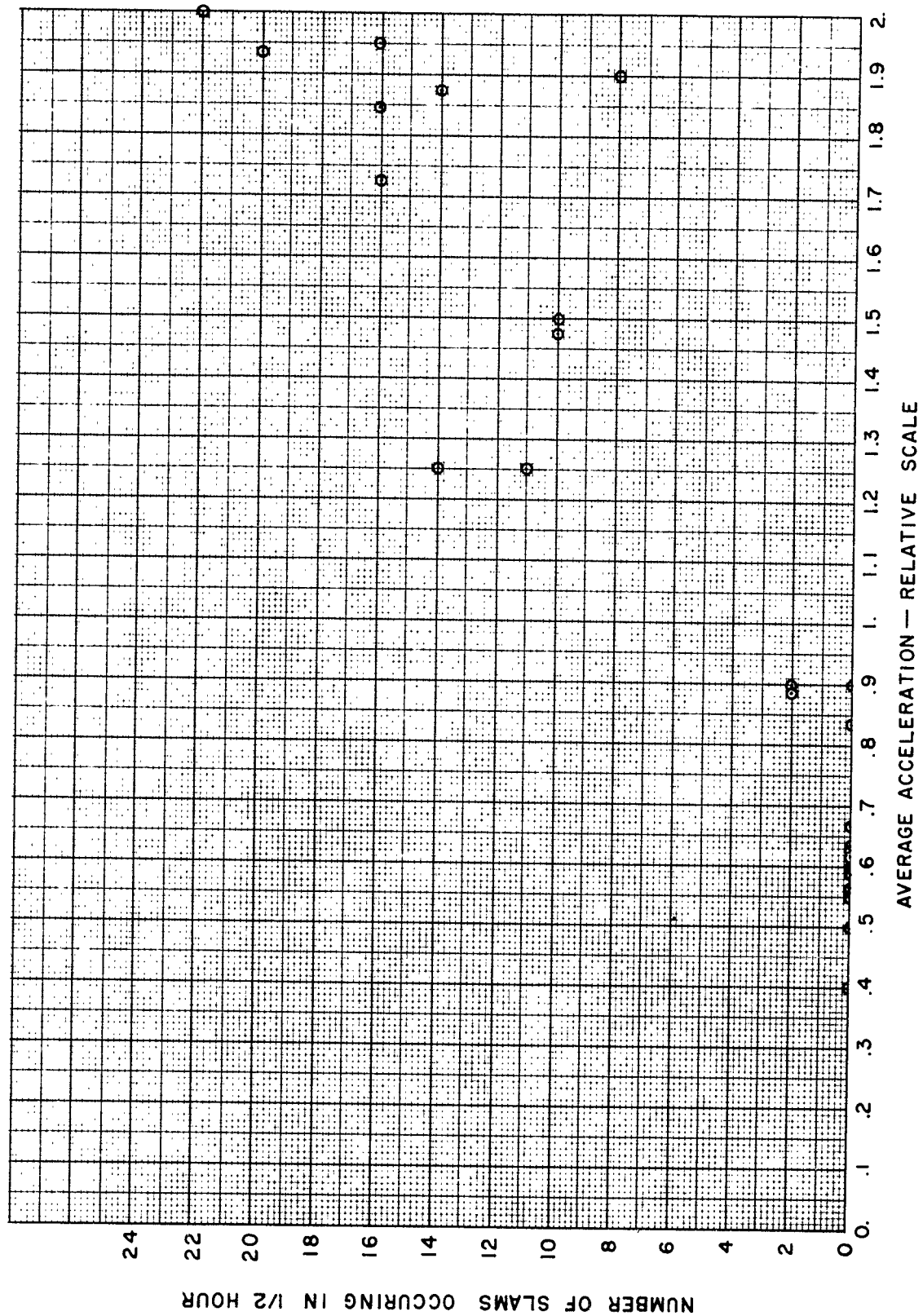
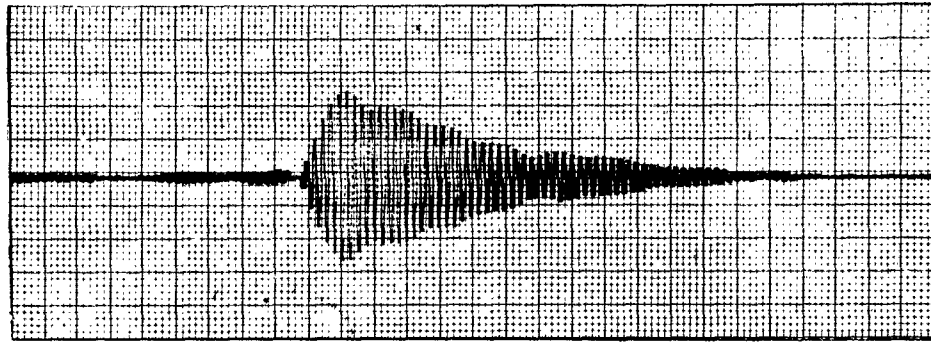


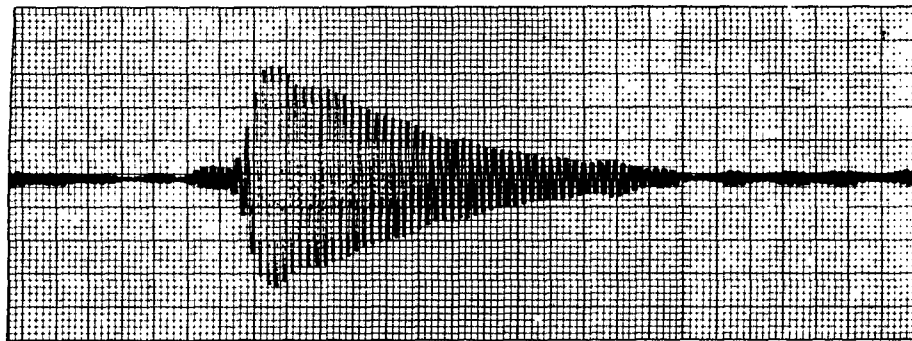
Figure 77. Number of Slams Occurring in One Half-Hour as a Function of Total Acceleration



Figure 78. Spray Probably Caused by a Slam



$Q \approx 66$



$Q \approx 70$

Figure 79. Typical Slam Records Used to Determine the Q of the Ship



Figure 80. USS Santee in a Storm

section X supplementary topics

In the course of any program such as the one covered by this report, numerous topics inevitably develop which are not of primary importance with regard to the principal investigation, but are interesting, and possibly of considerable worth to investigators working on related problems. This chapter is devoted to a brief discussion of three such topics: The possibility of obtaining motion records with a minimum of equipment; the existence and location of a point of minimum average acceleration; and the spectrum of the roll motion.

It was tacitly assumed in the earlier discussions of techniques for recording ship motion that the budget available was ample. Unfortunately, this is not always the case; however, it is possible to record useful information with a much more limited expenditure. The motion records in Figures 81 and 82 were recorded directly in graphical form aboard ship. The only equipment actually carried aboard consisted of an accelerometer and an Esterline Angus pen recorder. Batteries, a Fairchild linear potentiometer, a synchro, hook-up wire, etc., were obtained aboard ship. A Mark 6 stable element was utilized as the sensing device in obtaining the pitch record during landing operations. The synchro was driven by the 36-speed level output. The potentiometer was coupled to the selsyn shaft by a mechanical coupling made in the ship's machine shop. The pen recorder was operated directly from the potentiometer, power being supplied by the borrowed batteries.

The eight-hour acceleration record was obtained by operating the pen recorder directly from the accelerometer. This installation was made under the observer's bunk.

Graphical records are not suitable for data reduction techniques involving electronic analogue computation, such as were described in previous chapters. However, there is much useful information which may be gained by study of graphical records. In addition, digital-to-analogue conversion techniques could be applied to the graphical data

on a point-by-point basis, or the data could be transcribed onto magnetic tape directly by following the curve with a manually operated stylus mechanically coupled to a linear-travel potentiometer. The latter method was used in the early stages of this program to transcribe graphical records supplied by the British Admiralty. Thus, somewhat limited, but nevertheless satisfactory motion records may be obtained with installations far less complicated than the one made on the U.S.S. Oriskany.

The second topic for discussion is the existence and location of a point of minimum average acceleration. If such a point existed, it would be a preferred location for gyros, stable elements, and other equipment which is likely to be adversely affected by accelerations. It would also be the best place to go when threatened with sea sickness.

The manner of determining the location of the point of minimum average vertical acceleration is not difficult. It was stated previously without proof that pitch acceleration could be obtained by subtracting the signals of the forward and aft accelerometers. This will now be demonstrated as a preliminary to showing how the vertical acceleration at any point on an axis through two accelerometers may be obtained.

Figure 83 depicts two accelerometers mounted on a line parallel to the longitudinal axis of a ship. The accelerometers are roll stabilized only. The ship is involved in characteristic motion which may be described over a short interval of time as a vertical translation, in conjunction with a rotation. Arbitrarily the point marked "0" is taken as the center of rotation. The arcs r and s through which the instruments move during the pitching are given by:

$$r = b\psi \text{ and } s = -a\psi$$

The accelerations are:

$$\ddot{r} = b\ddot{\psi} \text{ and } \ddot{s} = -a\ddot{\psi}$$

When the two motions take place simultaneously, the measured accelerations are, to a good approximation, $B = b\ddot{\psi} + \ddot{h}$, and $A = a\ddot{\psi} + \ddot{h}$. The error in the last term of each expression being small if ψ is small.

The difference of the measured acceleration is:

$$B - A = (a + b)\ddot{\psi}$$

SECURITY INFORMATION—CONFIDENTIAL

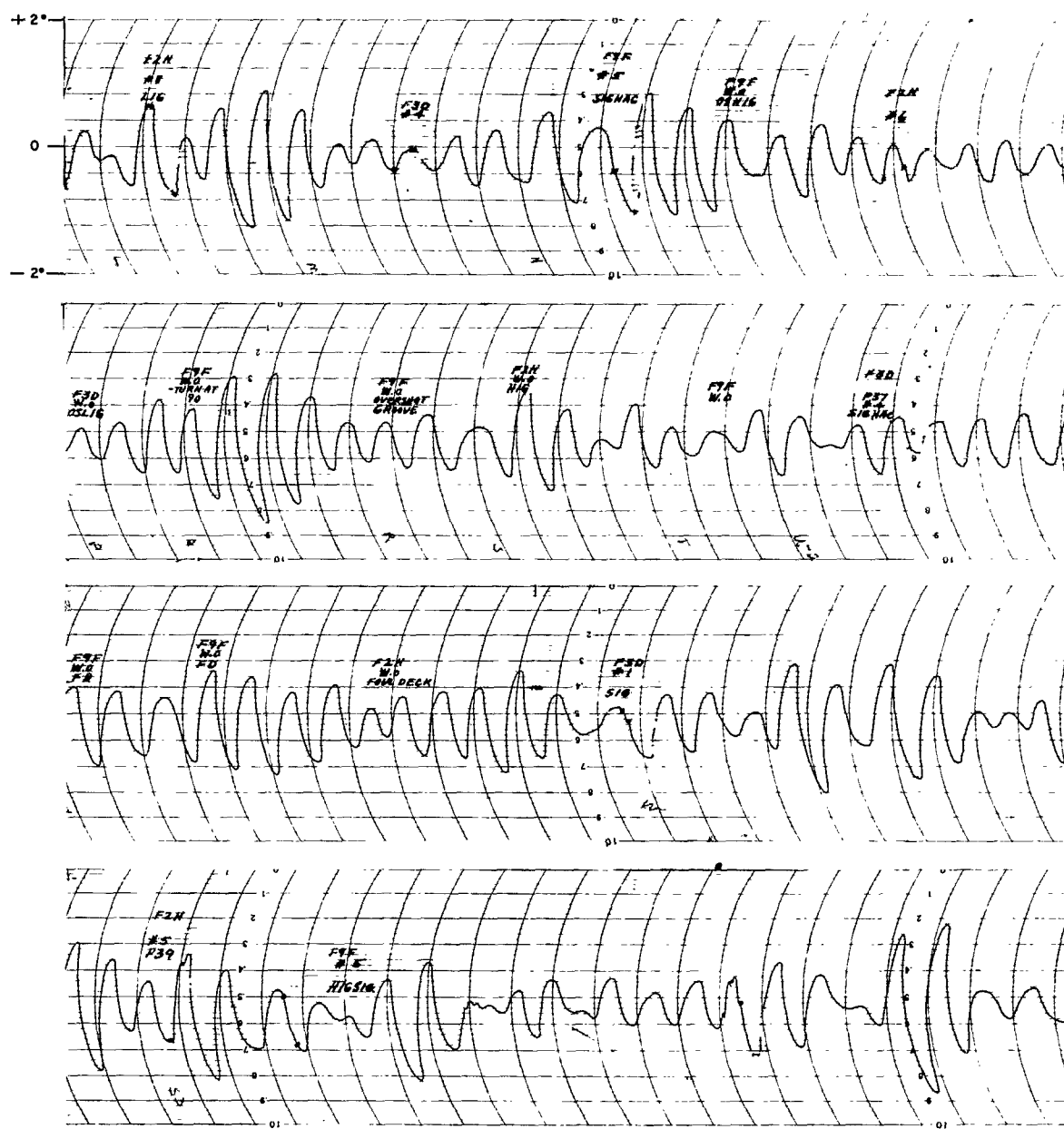


Figure 81. Pitch Motion of USS Wasp During Aircraft Recovery

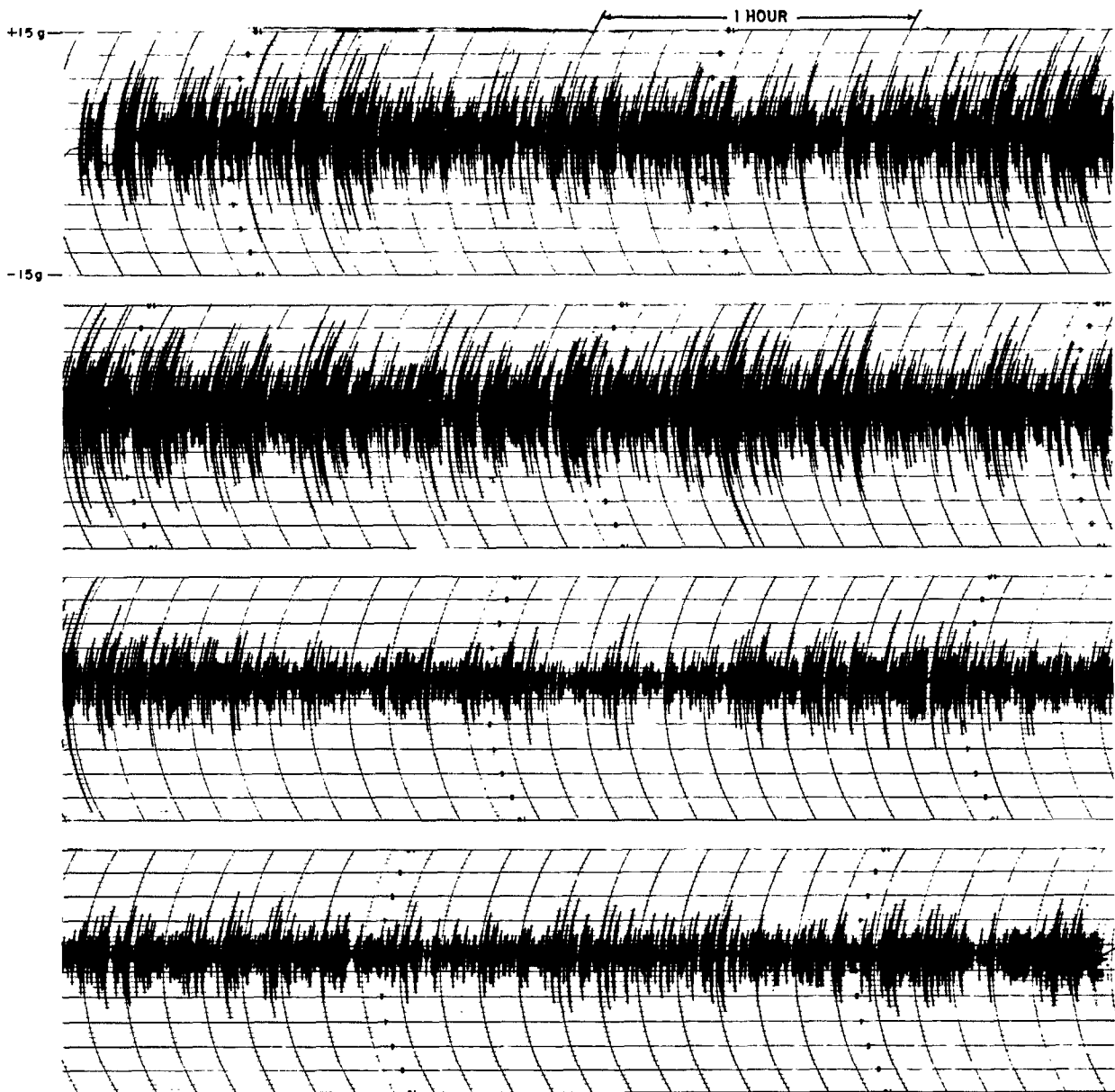


Figure 82. Aft Acceleration of USS Wasp

It is important that the numerical constant $(a + b)$ depend only on the separation of the two accelerometers, not on the location of point "0"; hence, the difference $B - A$ gives pitch acceleration times a constant which changes only when one of the accelerometers is moved.

Vertical acceleration at any point on the axis through A and B is found in much the same manner. For convenience, assume that the vertical acceleration at "0" is desired. The acceleration outputs are multiplied by the constants a and b to give:

$$aB = ab\ddot{\psi} + a\ddot{h}, \text{ and } Ab = -ab\ddot{\psi} + b\ddot{h}$$

adding these expressions yields:

$$aB + Ab = (a + b)\ddot{h}$$

Again it is found that the constant on the right hand is dependent only on the separation of accelerometers, and not on the particular choice of the point "0".

The average vertical acceleration at each of ten points, equally spaced along the deck, was determined by rectifying the vertical acceleration signals aB and Ab and integrating over a half-hour period. The equipment used is shown in Figure 84. The resistance R_1 and R_2 divide the total resistance of the potentiometer in the same ratios that a and b divide the total length of the deck. The results obtained for several tapes are plotted in Figure 85. It is noticed that the average vertical acceleration is at a minimum approximately two-thirds of the distance aft of the forward perpendicular. This result agrees with the findings of previous investigators.

There are three principal sources of error in this method, none of which, however, is considered prohibitively large. The error in \ddot{h} has already been mentioned. A second error is introduced by considering the ship as a rigid body. It was shown in the preceding chapter that this is not a good assumption when slamming takes place. However, it is believed to be reasonable in the absence of excessive slamming. The accuracy may easily be checked by a third accelerometer located at some convenient point between the other two. The third source of error is the inherent inaccuracies encountered in recording ship motions and reproducing the recorded signals in useful form. Methods of minimizing errors of this type were treated in the section on Accuracy.

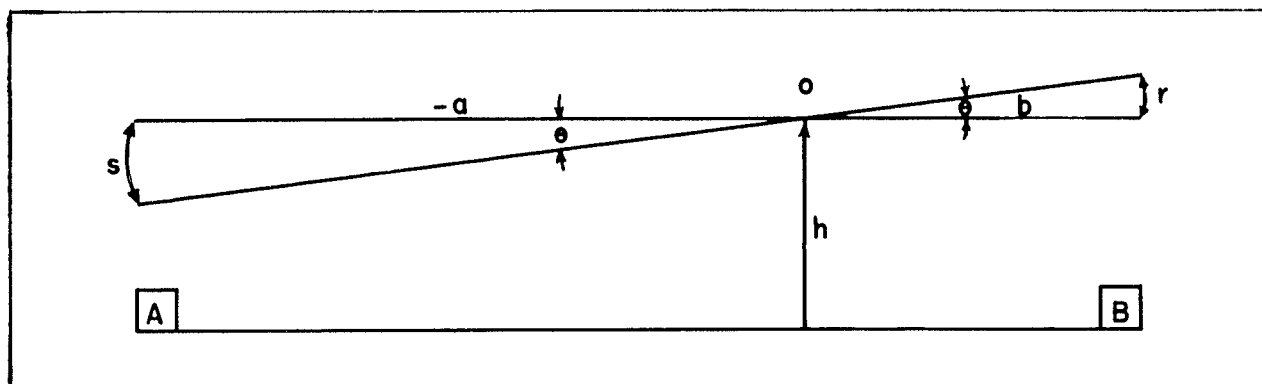


Figure 83. Method of Determining Pitch Acceleration

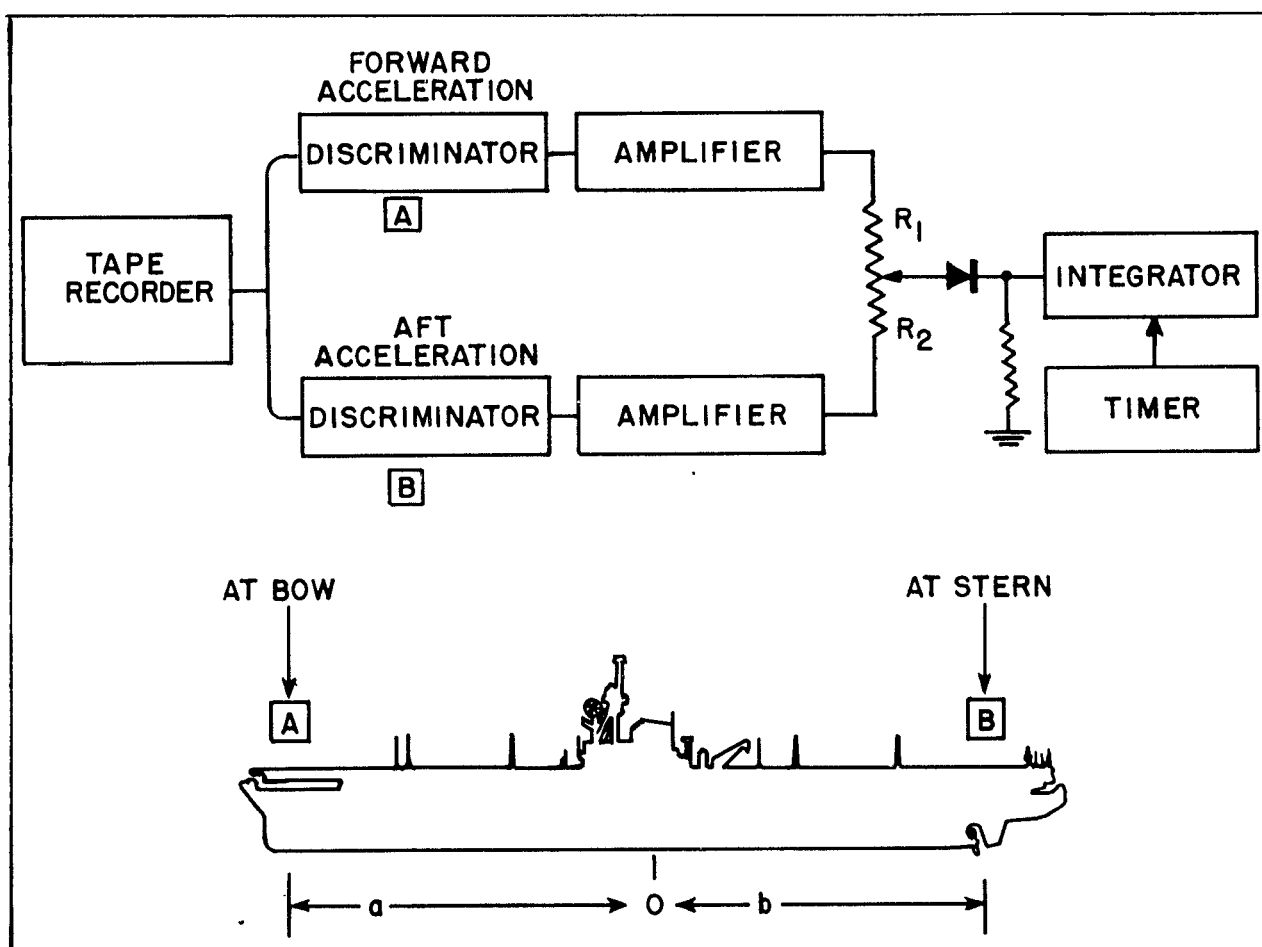


Figure 84. Method of Determining Average Vertical Acceleration

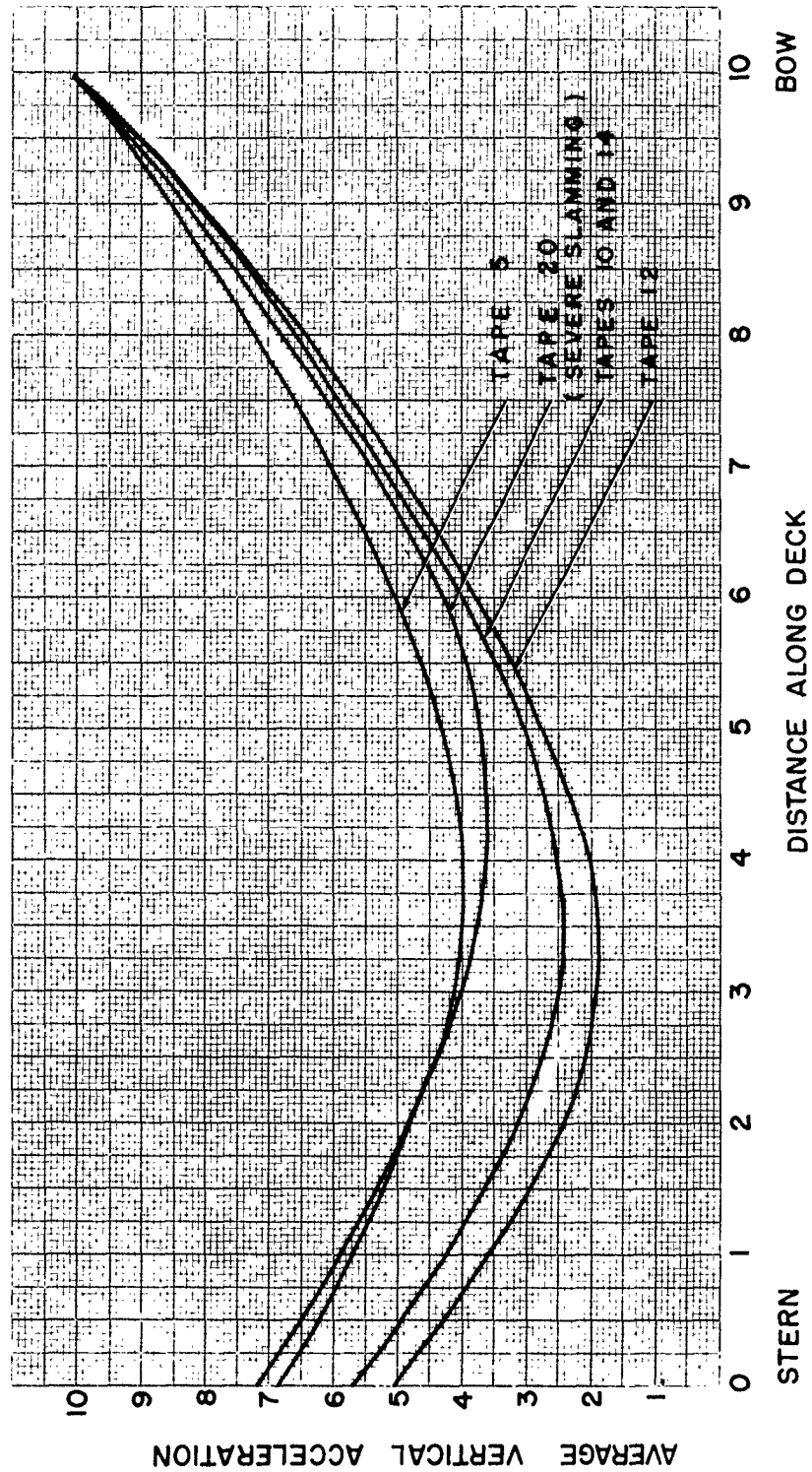


Figure 85. Average Vertical Acceleration

The last topic which will be discussed in this section is the roll spectrum shown in Figure 86. This spectrum was obtained by the same technique described previously for obtaining pitch spectra by use of the REAC computer. The surprising feature of this spectrum was the extremely sharp peak, which occurs at a frequency of 0.065 cycles-per-second. This corresponds to a roll period of 15.4 seconds; a figure which is in good agreement with the value determined by inclination experiments.

The spectrum shown in Figure 86 does not cover a large frequency range as scattering of the plotted points became so large for frequencies above 0.2 cycles per second that further work appeared useless. Had two accelerometers mounted on a thwartship axis been used in recording the motion, the spectrum could have been obtained from roll acceleration as the pitch spectra were. Presumably the curve continues decreasing at the same rate. The peaks due to the vertical modes would be expected to appear decidedly attenuated, if at all, since the vibrations would affect both accelerometers nearly equally. Peaks caused by the low-order transverse modes might be recognizable.

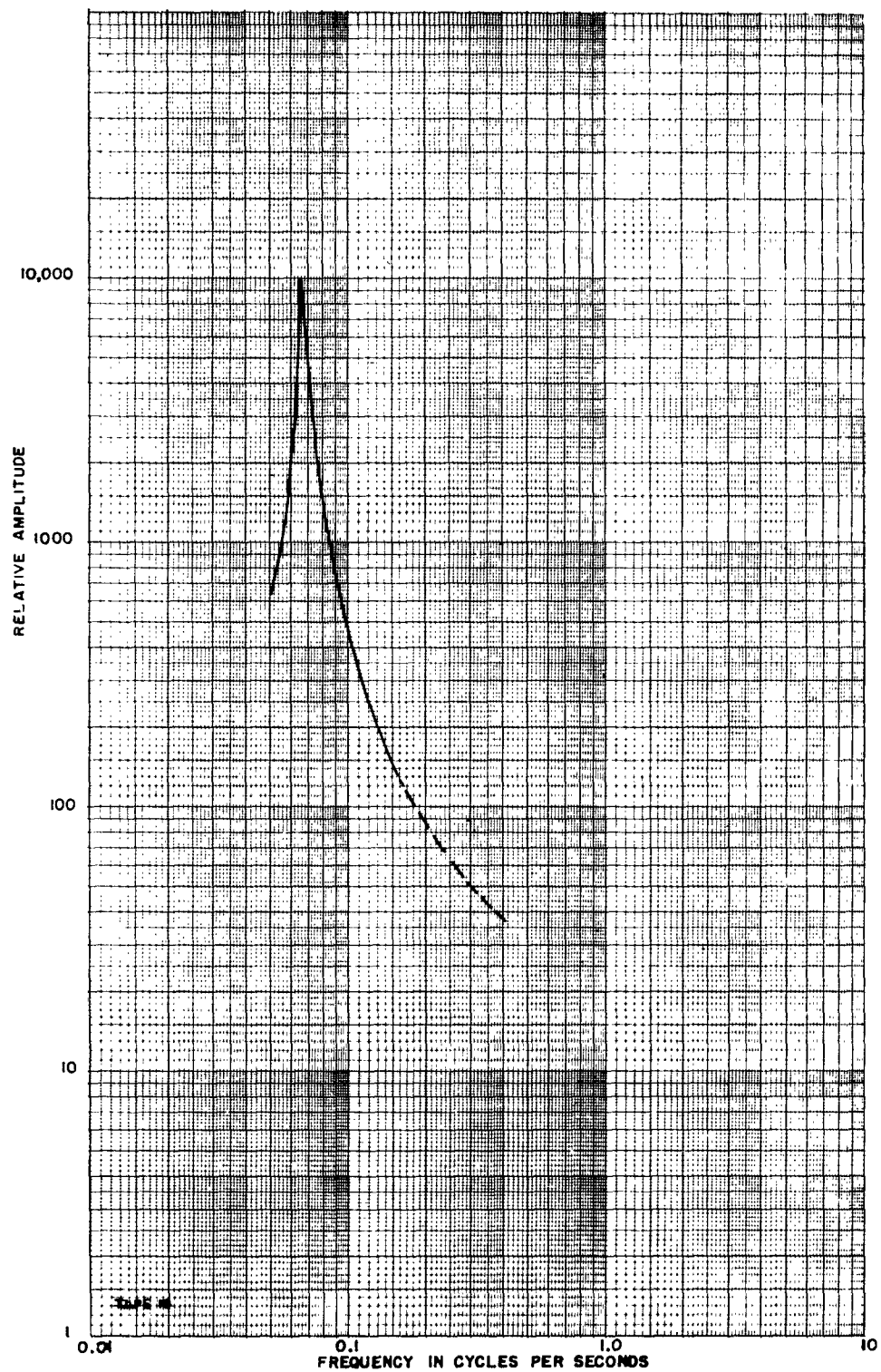


Figure 86. Roll Spectrum

section XI conclusion

The primary purpose of the investigation described in this report was a determination of the predictability of ship motion. The results, in terms of the prediction problem, will be treated in a later report. The specific results of this investigation concerning ship motion itself appear throughout this report, both in text and illustration.

The one general conclusion that can be drawn from this work is that the basic problem is one of measurement, and that progress towards a complete knowledge of the relationship between the sea, the ship, and the resulting motion, will come only with an increase in the accuracy with which the variables can be measured. The problem is an enormous and yet intriguing one.

On the basis of the work which has already been performed there are certain recommendations for future investigations which should be made.

1. Further work aboard ship with the most refined instruments now available, or that could be developed within time and economic limitations, coupled with careful placement of instruments to minimize contamination by ship vibration noise. This work might well be performed as a part of a carrier-landing system flight-test program.
2. Continuation of model basin studies with a much more completely instrumented model, preferably a model of the ship used for the work outlined in (1). This work would undoubtedly entail use of miniaturized instruments if the necessary equipment were to be installed in a model of manageable size.
3. Measurement of ocean surface spectra. At present this problem is one of instrumentation. Numerous methods have been tried with varying success, but there is general agreement that considerable development work is necessary.



Figure A-1. Pitch Angle and Roll Angle

appendix I definitions

The following definitions are standard definitions used in stable element work. The accompanying figure serves to illustrate the first two. (Figure A-1)

Roll Angle is the angle measured about an axis in the deck; the angle, measured in the athwartship plane perpendicular to the deck, between its intersection with the horizontal plane and with the deck plane. (Positive when starboard side of ship is up.)

Pitch Angle is the angle measured about an axis in the horizontal; the angle, measured about the intersection of the horizontal plane with the athwartship plane perpendicular to the deck, between the vertical plane and a plane perpendicular to the deck through this axis. (Positive when bow of ship is up.)

Level Angle is the angle measured about an axis in the horizontal plane and the deck plane measured in the vertical plane through the line of sight. (Positive when the deck toward the target is below the horizontal plane.)

Cross Level Angle is the angle measured about an axis in the deck; the angle, measured about the intersection of the plane of the deck with the plane through the line of sight perpendicular to the deck between the vertical plane and a plane perpendicular to the deck through this axis. (Positive if, when you face the target, the right-hand side of the ship is up.)

appendix II shipboard organization

This appendix is included solely for the sake of those who are undertaking ship motion recording programs and who have had no previous experience aboard naval vessels. Those readers who already know the difference between the Jimmy Legs and the Bow Hook may well omit this appendix.

It would be almost impossible, even if appropriate, to present a complete breakdown of the entire shipboard organization. Nevertheless it is well worth while to make a few remarks which may help someone overcome the awe and confusion he is bound to experience when he suddenly finds himself thrust into the highly organized chaos of shipboard activity. Accordingly, a rough picture will be presented of the organization as a whole, a brief description of the duties of the three most important persons — the captain, the executive officer, and the officer of the day, and a slightly more detailed discussion concerning the officers with whom a recording group will come into frequent contact.

The organization chart — Figure A-2— presents a picture of the organization as a whole. This chart does not depict the organization of any particular ship, nor is it intended to be either scrupulously accurate or detailed. The organization of every ship is different; it is the purpose here to present only the general framework. As examples of the variations which may be expected, some ships do not have a damage control department while other ships have both damage control and repair departments. Only ships primarily concerned with aircraft, such as aircraft carriers and seaplane tenders, have air departments. Frequently one officer will hold several jobs, but usually only jobs in one department. Thus the aerology officer, the photography officer, and the intelligence officer might be the same man.

All reports to the captain are made through the appropriate department head and the executive officer, with two exceptions. The

navigator makes his reports concerning the position and navigation of the ship directly to the captain, the officer of the deck likewise reports directly. When the captain is away from the ship, his duties are delegated to one of the senior officers, usually a department head, termed the duty commander. Under these circumstances the officer of the deck reports to the duty commander.

The captain holds complete responsibility for the safety and well-being of the ship and crew, as well as for the satisfactory operation of the ship. The only times the captain comes into direct contact with the crew are at inspection or at captain's mast, when the recalcitrant members of the crew are dealt with.

The executive officer is the captain's right-hand man. The mass of administrative detail necessary to keep a ship and crew functioning properly is carried out under the direction of the executive officer. The responsibility for seeing that the captain's orders are performed promptly and effectively rests solely with the executive officer. Customarily, the executive officer has no assigned duties as far as the navigation and operation of the ship is concerned, but he may on occasion take the bridge of his own volition in the captain's absence.

The officer of the deck is the name given to the officer who is in immediate, active charge of the ship. During his four-hour watch, the officer of the deck is subordinate only to the captain (or duty commander) and the executive officer. He is the immediate authority and is expected to handle not only the routine details which arise, but also the emergencies. At sea he stands his watch on the bridge, in port he is stationed on the quarter-deck. When going aboard ship, it is to him that everyone must present his credentials. The officer of the deck is easily recognized because by custom he always wears gloves and carries a spy-glass under his arm. He will inspect the newcomer's credentials, officially welcome him aboard, see that appropriate quarters are assigned to him, that his luggage is taken care of, and that the proper persons are informed of his arrival. If the mooring lines suddenly parted and the ship started drifting down the bay, the officer of the deck would be expected to cope with that situation. This gives a rough idea of the duties of the officer of the deck.

It would be ideal if a recording group could go aboard ship and carry out their complete recording program entirely under the auspices of a single department. This, unfortunately, is not the case. The group must depend on the cooperation of many different individuals in several departments. Accordingly, an account is made in the following paragraphs of some of the many facilities a recording group might wish to utilize, and whose permission would have to be obtained in each case.

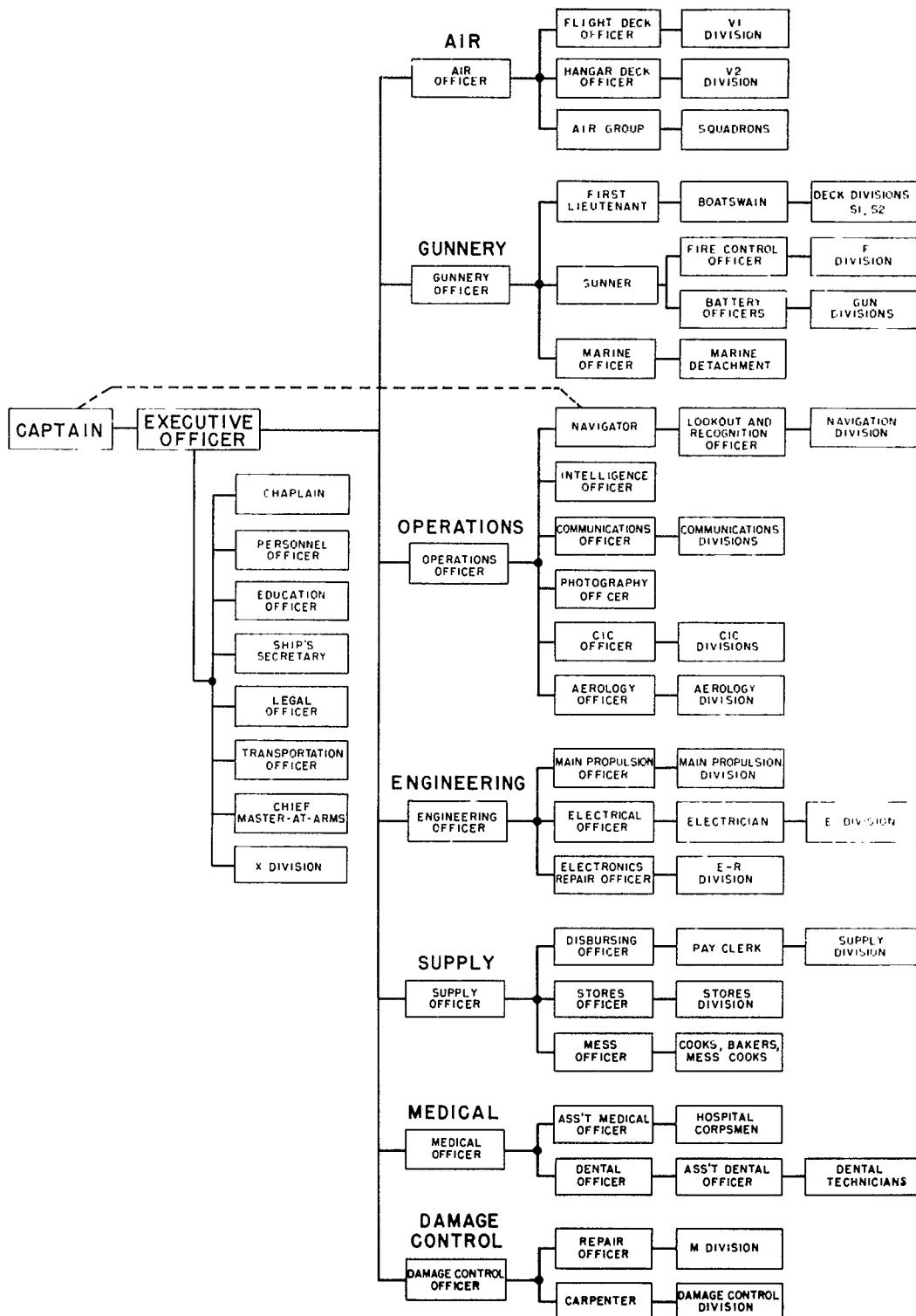


Figure A-2. Typical Shipboard Organization Chart

The stable element may come under the cognizance of either the Gunnery or Engineering departments. Stable elements such as the Mark 6 are customarily used for gun and director stabilization and therefore are operated and serviced by the F division which is part of the gunnery department. The Mark 8 Models 2 and 4 stable elements, however, are generally used to stabilize radar antennas, particularly the SP, hence they belong to the E-R division, which comes under the Engineering Department.

If the F division has cognizance of the stable element, arrangements can be made directly with the F division officer, and the petty officer in charge of the plotting room where the stable element is located, to disconnect or zero the stabilized devices during recording periods. If the stable element is used for the stabilization of antennas other than those associated with fire control radars, arrangements must be made with the department head responsible to have the antennas properly oriented during recording periods. In this instance, the E-R division cannot, in general, be responsible, although they have cognizance of the equipment. Radar operation is the direct responsibility of the Combat Information Center (CIC) officer, who reports to the Head of the Operations Department. Arrangements regarding the availability of the stable element for ship-motion recording must be made with these officers.

The gyro-compass is under the cognizance of the ship's electricians — E division, and arrangements for connecting to the own-ship's-course must be made with the E division officer and the petty officer, or chief petty officer, in charge of the gyro.

The Interior Communication (IC) gang is part of the E-division and is usually under the direction of one or two chief petty officers. This group is responsible for running all lines throughout the ship. Customarily a relatively large supply of portable cable is retained on board. Nevertheless, it is advisable to plan an installation far enough ahead of time to permit the CPO in charge of the IC gang to obtain additional cable, if necessary.

The general plans of the ship are kept in the log room, in the custody of the damage control officer. The general plans — in addition to the customary plan and elevation views, show isometric views of each deck, and are of great assistance in deciding on suitable instrument locations, cable runs, and other details. The damage control officer must check all proposed cable runs to insure that the watertight integrity of the ship is not violated. Certain hatches and watertight doors must be kept dogged while at sea and cable may not be run through them. Certain bulkheads may be cut through for cable

runs, but others may not. Much time can be saved by consulting the damage control officer as soon as the proposed cabling plan is laid out and in any event prior permission must be obtained before burning or drilling any part of the ship's structure, regardless of whether the work is done by ship's company.

There are many valuable small assistances which may be obtained from the E-R and E divisions. The former has cognizance of the majority of the ship's electronic test equipment and spare parts such as tubes and small components. Personnel with detailed knowledge of the radars associated with the stable element (when this is the case) come from the E-R division.

The E division, in addition to the functions mentioned, has charge of the battery locker, the electrical shop, the lighting shop, and most of the electrical equipment throughout the ship. The principal exceptions being the equipment which is primarily electronic, or which is associated with fire control systems and gun laying. Storage batteries of various capacities and up to 24 volts may be obtained from the battery locker, and returned for recharging when necessary. The electrical shop is equipped to handle all manner of electrical repair including rewinding jobs on all but the largest motors and generators.

Even small ships have reasonably well equipped machine shops capable of turning out accurately machined parts. The machine shop is operated by M division and is under either the damage control or the repair officer.

If the recording group does not choose to make its own observations during recording periods, this information may be obtained from the aerology group. This group operates under the Operations Department. Weather observations and data are recorded at regular intervals, depending on operations, and a complete weather map is made up, usually every six hours. An hourly or half-hourly record of the ship's position is also kept by this group. A complete record of ship's position and weather is maintained at the Bureau of Navigation in Washington, D.C.

The ship's course and speed, and the shaft-turns-per-minute are recorded in the quartermaster's log. This log is kept in two books, one containing the information for the 00-04, 08-12, 16-20 watches and the other containing the information for the 04-08, 12-16, 20-24 watches. It is more convenient at the conclusion of a recording period to wait until the next watch before copying out the course and speed data. In port, the quartermaster's log is transferred to the quarterdeck.

SECURITY INFORMATION—CONFIDENTIAL

Every compartment aboard ship is the responsibility of one of the divisions. When instruments are installed in a compartment, the division petty officer having charge of that space should be notified and given detailed instructions as to what action should be taken in the event of damage, overheating, or other emergencies.

It should be kept in mind that all work done by members of ship's company for the motion-recording group is in addition to regularly assigned duties. Members of the recording group should make every effort to keep the increase in work load, occasioned by their presence aboard, to an absolute minimum.

acknowledgments

The work described in this report would have been impossible were it not for the contributions and cooperation of many individuals and groups. Particular mention should be made of the excellent work performed by the members of the British Admiralty Ship Welding Committee in connection with the instrumentation and sea trials of the S.S. Ocean Vulcan. Another important contribution originating in Great Britain is the study performed by the Naval Aircraft Research Committee of the Aeronautical Research Council and reported by J. L. Bartlett. A great deal of assistance has been received from Henry D. Sheitelman, Bureau of Ships, who has administered the contract under which this work was performed. Mr. B. K. Couper, Bureau of Ships, has given considerable help with the oceanographic work. Particular thanks are due the officers and enlisted men of the Aircraft carriers Midway, Kula Gulf, Cabot, Saipan, Wasp and Oriskany who cheerfully performed the extra work necessitated by the presence of a motion-recording group on board. Contributions by the David Taylor Model Basin and the Naval Research Laboratory are discussed in the body of the report.

bibliography

- Bartlett, J. L., Ship Motion, Naval Aircraft Research Committee (Great Britain), Aeronautical Research Council, No. 13989, F.A.R. 267, 5 May 1951.
- Bigelow, Henry B., and Edmondson, W. T., Wind Waves At Sea Breakers and Surf, U. S. Navy Hydrographic Office, H. O. 602, Washington, D.C., 1947.
- Bull, F. B., Baker, J. F., Johnson, A. J., Ridler, A. V., The Measurement and Recording of the Forces Acting on a Ship at Sea, Read at the autumn meeting of the Institution of Naval Architects, 21 September 1948.
- Davidson, Martin, D.Sc., T.P.A.S., The Gyroscope and Its Applications, Hutchinson's Scientific and Technical Publications, London, 1947.
- Kent, J. L., C.B.E., The Causes and Prevention of Slamming of Ships in a Seaway, Transactions of the Institute of Naval Architects, Vol. 91, 1949, pp. 451-459.
- McGoldrick, R. T., Investigation of Propeller-excited Vibration on U.S.S. Oriskany (CV-34), David W. Taylor Model Basin, Report C-144, May 1951, (Confidential).
- Niedermair, J. C., Ship Motions, Transactions of the Institute of Naval Architects, Vol. 93, 1951, pp. 137-152.
- Sverdrup, H. V., Johnson, Martin W., Fleming, Richard, The Oceans, Their Physics, Chemistry and General Biology, Prentice Hall, Inc., New York, 1942.
- Weinblum, G., and St. Denis, M., On The Motion of Ships At Sea, Transactions of the Society of Naval Architects and Marine Engineers, 1950.